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# Water Resources of Cape Cod

## Water Use, Hydrology, and Potential Changes in Ground Water Levels

October 1994

Massachusetts Executive Office of Environmental Affairs
Department of Environmental Management
**Office of Water Resources**

*William F. Weld, Governor ■ Argeo Paul Cellucci, Lt. Governor ■ Trudy Coxe, Secretary ■ Peter C. Webber, Commissioner*

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# WATER RESOURCES OF CAPE COD:

## WATER USE, HYDROLOGY, AND POTENTIAL CHANGES IN GROUND WATER LEVELS

## EXECUTIVE SUMMARY

This report is a technical evaluation of the potential changes in water levels on Cape Cod as a result of several scenarios of future water use and recharge. The scope of the report is regional, and, except as noted, applies to town or multi-town areas rather than individual bodies of water. A key finding is that on a regional basis, assuming that the ground water is adequately protected, there is sufficient water available for the future needs of Cape Cod communities, even under a high use and low recharge scenario. With high use and drought conditions, localized drawdowns of surface and ground water can be expected.

### Natural Resources, Demography and Water Use

- The Cape's natural resources provide habitat for a wide variety of fisheries and wildlife. These resources include kettlehole ponds, wetlands, coastal streams, and seven designated Areas of Critical Environmental Concern (ACEC).
- The 1990 federal census population of Cape Cod was 186,605. Summer population is estimated at 512,520, an increase of 175 percent.
- Year-round population is expected to increase from 186,605 in 1990 to 229,437 in 2020, while summer population is expected to rise from 512,520 to 594,831.
- Off-season (September to May) base average day demand (ADD) on public water supplies is 18.68 mgd. By 2020, off-season ADD is projected to reach 27.76 mgd.
- In-season (June, July and August) base ADD is 38.73 mgd. By 2020, in-season ADD is projected to reach 54.38 mgd.
- Estimated water needs of industrial and commercial users on Cape Cod are 0.91 mgd.
- Cranberry cultivators on Cape Cod are estimated to use 9.40 mgd annually.
- Water is returned to the aquifer lenses by on-site septic systems and subsurface disposal of treated municipal sewage. In conformance with the state Ocean Sanctuaries Act, no wastewater is discharged directly to the ocean.

### Cape Cod Hydrology

- Approximately 96 percent of available water on Cape Cod is in ground water.
- Annual average rainfall is 45 inches.
- Cape Cod consists of six hydraulically independent ground water flow cells, or lenses, separated by tidal rivers.
- Of the six flow cells, only three, the West Cape, East Cape, and Truro, currently have sources of public water supply. Two others have potential to provide future supplies.
- Sixty-six percent of Cape Cod's total public water supply was drawn from the West Cape flow cell in 1989, thirty-one percent was drawn from the East Cape flow cell, and approximately three percent of the Cape's total public water supply comes from the Truro flow cell.

## Ground Water Modeling

Five flow cells with potential for public water supply development were analyzed for potential changes in ground water levels using a model developed by the U.S. Geological Survey in cooperation with the DEM Office of Water Resources. Each flow cell was modeled using both average precipitation and drought recharge conditions. Current and projected 2020 in-season and off-season water needs were used to simulate well usage and probable impacts on water levels in modelled water bodies. The model grid size used is ¼ mile (1,320 ft.$^2$).

### Summary of model results for West Cape and East Cape flow cells

The West Cape and East Cape Flow cells are the major water supply cells in the basin, providing a combined estimated total of 97% of the Cape's public water supply. The report compares the changes in ground water levels resulting from increased pumping (current and 2020 water needs) and normal and drought recharge conditions. Modelling for these cells shows that the impact of drought recharge conditions on ground water levels has a much greater impact than does increased pumping:

In the West Cape Lens, water withdrawn by public water supply agencies averages 25.76 mgd, in-season, and 12.86 mgd, off-season.

- Under current demand and *drought recharge conditions*, the average water table level for the flow cell was 3.93 feet lower than under normal recharge conditions.
- Water needs in 2020 are expected to increase nearly 45 percent in-season and nearly 51 percent off-season. Running the model with these increased 2020 demands under *normal recharge conditions*, there is no measurable change in water table levels.

In the East Cape Lens, water withdrawn by public water supply agencies averages 11.65 mgd during the in-season and 5.19 mgd in the off-season.

- Under current demand and *drought recharge conditions*, the average water table level for the flow cell was 3.4 feet lower than under normal recharge conditions.
- Water needs in 2020 are expected to increase nearly 35 percent in-season and nearly 49 percent off-season. Running the model with these increased 2020 demands under *normal recharge conditions*, the decline in water table levels averages 0.3 feet.

While the modelled changes are not considered significant from a regional perspective, in some cases, pumping wells can have significant impacts on nearby water bodies and may affect specific biological resources. With additional modelling and more localized hydrogeological data, more precise estimations can be made of potential changes in ground and surface water levels.

**Applications of this study**

Because the models are dynamic tools, they can be updated and modified to meet a large number of possible scenarios associated with the planning needs of a particular project. For instance, communities and DEP may be better able to evaluate Water Management Act permit applications and evaluate the potential impacts on individual bodies of water from additional well withdrawals. Communities planning to develop new supplies would be able to evaluate various locations and withdrawal volumes and their impacts on ground and surface water. From a regional planning perspective, adjacent communities would be better able to understand the impacts of pumping on each others' wells and water bodies. Based on these studies, it may be possible to clarify the impacts of the scenarios on biological resources in and around ponds and other water bodies.

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# WATER RESOURCES OF CAPE COD:

## WATER USE, HYDROLOGY, AND POTENTIAL CHANGES IN GROUND WATER LEVELS

## INTRODUCTION

### A. River Basin Planning Program: Purpose and Process

River basin plans are intended to provide a technical reference point for water resources planning, management, and decision-making at the local and basin-wide level. They provide the basic data and analysis needed to describe the hydrologic characteristics of the basin; to identify potential water resource problems; to resolve outstanding issues of resource use and protection; to inform regulatory activities; and to develop recommendations for community and regional water supplies and demand management activities.

The Massachusetts Water Resources Commission (WRC) has the primary responsibility for determining the state's water resources policy and directing the water resources planning activities for the Executive Office of Environmental Affairs. The Office of Water Resources (OWR), in the Department of Environmental Management, provides technical staff support to the Commission and is responsible, through the Commission, for long-range water resources planning for the Commonwealth.

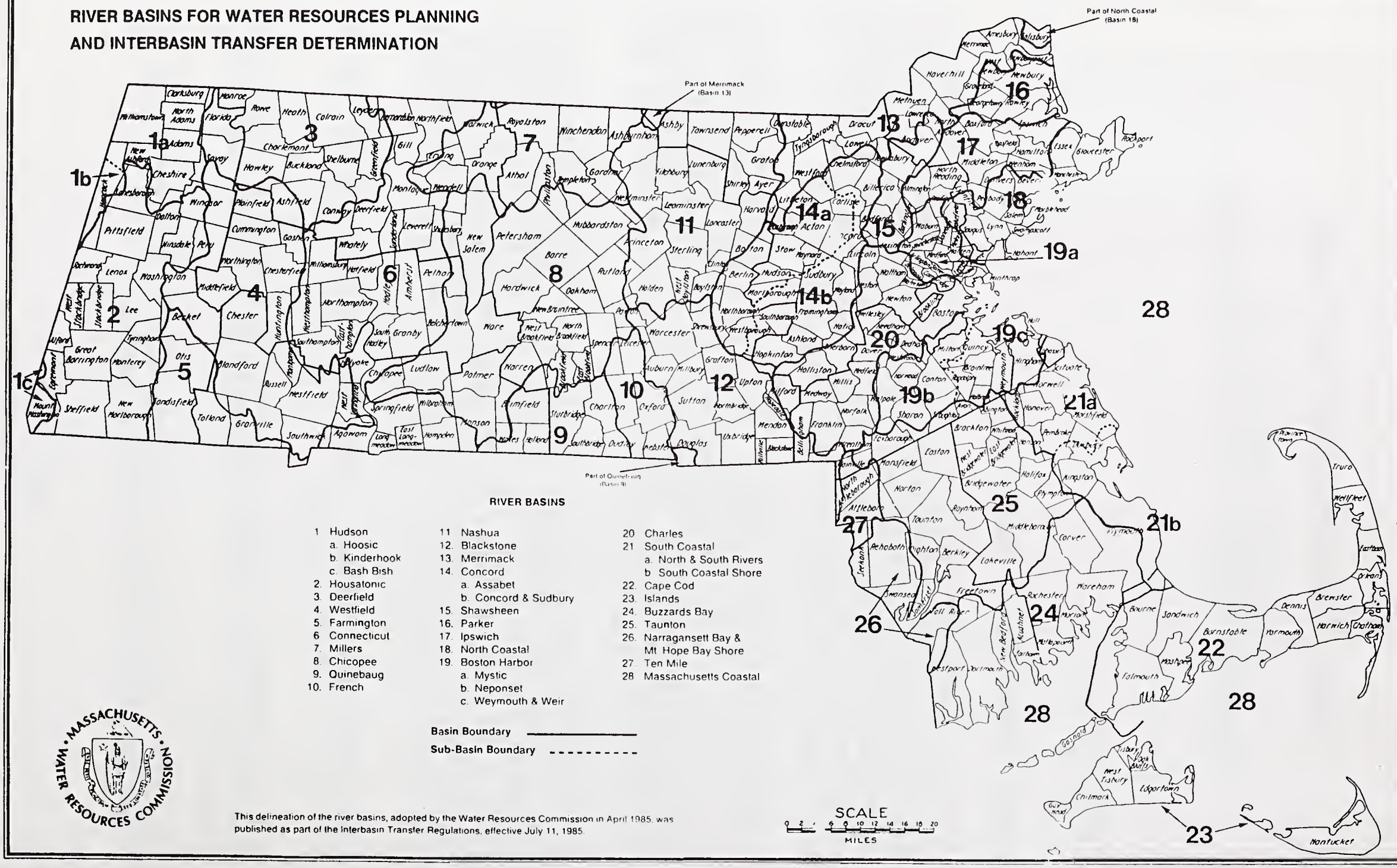
Pursuant to the Water Resources Planning Regulations (313 CMR 2.00), adopted by the Commission, OWR develops basin plans for each of the twenty-seven major river basins in the Commonwealth (Figure 1). The basin planning program is part of the state's overall goal of insuring that water is available in sufficient quantity and quality to meet current and future consumptive and non-consumptive water needs. The basin planning process includes local, regional, and state assessments of water needs and the availability of water resources and reflects the state's water resources management policies:

- Supply Management  Utilizing local sources (those within a river basin) first and protecting all sources of water supply;

- Demand Management  Practicing water conservation, full-cost pricing and other measures described in the 1992 *Water Conservation Standards for the Commonwealth of Massachusetts*;

- Administrative Management  Strengthening local water management through financial and technical assistance and planning guidance.

# RIVER BASINS FOR WATER RESOURCES PLANNING AND INTERBASIN TRANSFER DETERMINATION




**RIVER BASINS**

1. Hudson
   a. Hoosic
   b. Kinderhook
   c. Bash Bish
2. Housatonic
3. Deerfield
4. Westfield
5. Farmington
6. Connecticut
7. Millers
8. Chicopee
9. Quinebaug
10. French
11. Nashua
12. Blackstone
13. Merrimack
14. Concord
    a. Assabet
    b. Concord & Sudbury
15. Shawsheen
16. Parker
17. Ipswich
18. North Coastal
19. Boston Harbor
    a. Mystic
    b. Neponset
    c. Weymouth & Weir
20. Charles
21. South Coastal
    a. North & South Rivers
    b. South Coastal Shore
22. Cape Cod
23. Islands
24. Buzzards Bay
25. Taunton
26. Narragansett Bay & Mt. Hope Bay Shore
27. Ten Mile
28. Massachusetts Coastal

Basin Boundary ————————

Sub-Basin Boundary - - - - - - - - - -

MASSACHUSETTS WATER RESOURCES COMMISSION

This delineation of the river basins, adopted by the Water Resources Commission in April 1985, was published as part of the Interbasin Transfer Regulations, effective July 11, 1985.

SCALE
0 2 4 6 8 10 12 14 16 18 20
MILES

**Executive Office of Environmental Affairs • Water Resources Commission**

Prepared by the Department of Environmental Management • Division of Water Resources

Figure 1

Based on the information and technical analyses in the basin plan and additional available data, OWR staff works with local or regional groups and other state agencies to develop recommendations in response to specific water management problems or issues. Staff works with those groups or agencies to identify the potential impacts of various options on the physical systems, and to develop a recommended course of action.

## B. Developing the Concept of Basin Planning

Massachusetts environmental agencies plan, manage, analyze, permit and regulate water resources in the context of river basins, as set out in four key legislative and policy mandates.

The **Massachusetts Water Supply Policy Statement--1984 update**, produced by the Water Resources Commission (WRC) and approved through the MEPA process, emphasizes the need for long-range, statewide planning (under the umbrella of 313 CMR 2.00--see below) and adopts supply and demand management policies in a balanced approach aimed at providing for multiple uses, protecting quality, assuring availability for consumptive and non-consumptive needs, and supporting local capabilities to plan, construct, manage and protect water supplies.

The **Water Resources Management Planning regulations** make the Water Resources Commission (WRC) responsible for developing "comprehensive water resources management plans for Massachusetts and to assure that such plans are based on local, regional and state assessments of water needs and water resources; are in conformance with the Massachusetts Water Supply Policy; and are based on adequate data, aggregated by river basins" (313 CMR 2.00, adopted in 1979 and updated 12/31/83).

The basin planning regulations promote the concept of a basinwide, comprehensive and integrated approach to all aspects of planning and management of the state's water resources. They provide that when the plans are adopted by the Commission, they "shall be considered by state agencies in all decisions relating to water resources management, including allocation of resources, expenditure of funds and the making of legislative recommendations affecting policies and programs. No such decisions contrary to said plans should be finally made without the concurrence of the Commission, and no proposed actions contrary to such plans shall be endorsed by the Commission".

The **Interbasin Transfer Act** (Ch. 658, Acts of 1983 and 313 CMR 4.00) was enacted to protect the water resources of each basin and promote its efficient use by requiring the WRC to regulate the transfer of water or wastewater between or among the basins. The 27 river basins of the Commonwealth are delineated in 313 CMR 4.00, the Interbasin Transfer Regulations and the accompanying map. Key components required that the applicant demonstrate that all viable sources within a basin had been investigated and protected; that all water conservation efforts had been implemented; and that a reasonable instream flow is maintained in the donor basin.

The **Water Management Act** (Ch. 592 Acts of 1985) and regulations (310 CMR 36.00) were established within the Department of Environmental Protection to register and regulate the withdrawals of water above a threshold quantity in order to "document baseline water use in the Commonwealth and begin the process of comprehensive management of the surface and groundwater of the Commonwealth". The permit program was set up in the regulations to "assist the Department in the comprehensive management of the Commonwealth's water resources within its river basins in a manner which ensures an appropriate balance among competing water withdrawals and uses, as well as preservation of the water resource itself".

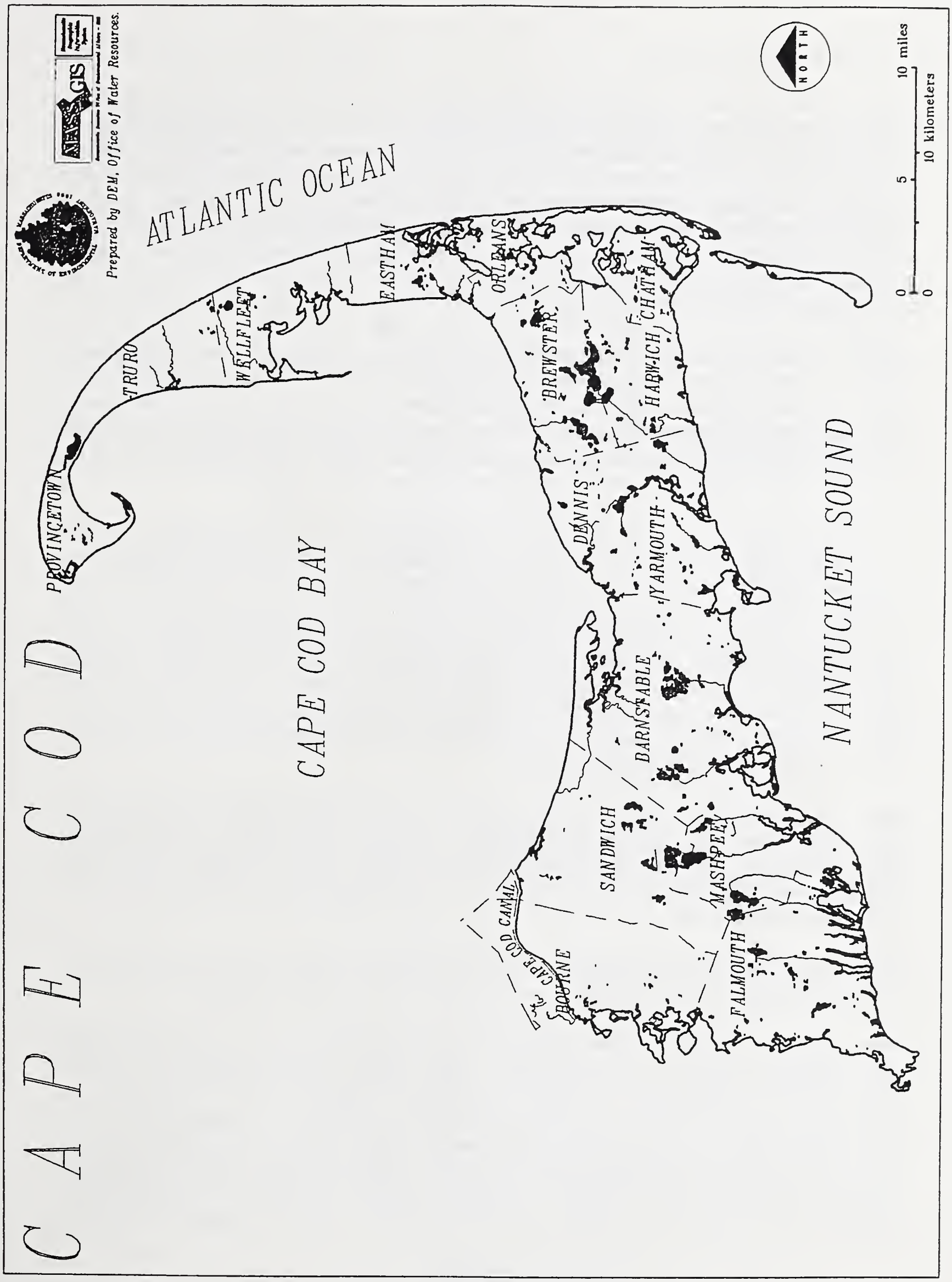
## C. Study Area Description

Cape Cod is one of the most prominent geographic features of Massachusetts. Extending into the Atlantic Ocean from southeastern Massachusetts, the Cape is surrounded by Cape Cod Bay on the north and west, the Atlantic Ocean to the east, Nantucket Sound to the south, and Buzzards Bay to the southwest. The Cape is separated from the mainland by a man-made canal located in the town of Bourne. (Figure 2). The peninsula measures about 40 miles from east to west and 25 miles from north to south, and has an area of 440 square miles. Elevations range from sea level to 309 feet above sea level. Mean annual precipitation ranges from 40 inches per year in the eastern portion to 47 inches per year in the west.

Under the Massachusetts River Basin Planning program, Cape Cod is classified as a river basin, although there is no prominent river which drains the entire land area. It was included because of its unique hydrogeological characteristics. The Cape Cod aquifer has been designated as a sole source aquifer by the US Environmental Protection Agency, meaning that it is the only source of potable water for the residents, businesses, and visitors to the area. Sole source designation is granted to an aquifer on the basis of its being needed to supply 50 percent or more of the drinking water for its service area. An additional criterion is that there are no reasonably available water supply alternatives should the aquifer become contaminated. All federally-funded projects within a designated sole source aquifer must be reviewed by the EPA. This review could either prevent a commitment of federal funding to those projects deemed to have the potential for contaminating the aquifer, or cause the redesign of such projects (USEPA 1987).

The 15 communities located on Cape Cod (Barnstable County) which make up the study area are: Barnstable, Bourne, Brewster, Chatham, Dennis, Eastham, Falmouth, Harwich, Mashpee, Orleans, Provincetown, Sandwich, Truro, Wellfleet, and Yarmouth. The section of Bourne located north of the Cape Cod Canal is hydrologically distinct from the rest of Cape Cod; therefore, this part of Bourne, together with the two water districts which serve the area, will not be considered in this study.

Figure 2


CAPE COD
Prepared by DEM, Office of Water Resources.
ATLANTIC OCEAN
CAPE COD BAY
NANTUCKET SOUND
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
CHATHAM
HARWICH
DENNIS
YARMOUTH
BARNSTABLE
SANDWICH
MASHPEE
FALMOUTH
BOURNE
CAPE COD CANAL
NORTH
0 5 10 miles
0 10 kilometers

## D. Description of the Study

The main focus of this report is a technical evaluation of the potential changes in water levels on Cape Cod as a result of several scenarios of future water use and recharge. The first section provides information from the Department of Fisheries, Wildlife and Environmental Law Enforcement on the key natural resources, specifically fish and wildlife populations that may be affected by changes in pond levels or stream flows. The first section also includes water use data for consumptive and non-consumptive uses of ground and surface waters, water demand information on public water supply sources for those communities with public water supplies, 1990 federal census figures, 1995-2020 population forecasts, and 1995-2020 projected water needs.

Water use data was obtained from the superintendents of 18 public water supply agencies and from the Division of Water Supply (DWS), Massachusetts Department of Environmental Protection (DEP). In 1988 and 1989, water supply superintendents reviewed, updated, and verified the 1988 Municipal Water Resource Management Plan questionnaire. To obtain more detailed information on water use and supply, OWR conducted personal interviews and telephone conversations with each water superintendent.

Population projections for both year-round and seasonal time periods are based on studies by the Cape Cod Commission (CCC) and the Massachusetts Institute for Social and Economic Research, and the 1990 census. Water demand projections for 1995-2020 were developed using the WRC-approved methodology outlined in Appendix A. This methodology is based on assumptions concerning population growth and water use in the basin during the period 1989-2020. This report will use the terms "year-round", meaning those persons who list Cape Cod as their primary residence, and "summer", meaning those people who have a second home on the Cape or are visiting for a portion of the year. These terms describe population only. Water use will be designated by the terms "off-season" and "in-season", as defined below.

Because Cape Cod experiences two distinct water demand regimes, average day demand was projected for both the nine month "off-season" (January through May and September through December) and the three month "in-season" (June, July and August). Base water demand for each community was calculated for the two seasons using water demand for the years 1986 through 1990.

The second section of this report describes the ground water model used in the analysis and the impacts on pond and stream levels as a result of the modeled scenarios.

There are many important issues related to water resources on the Cape, however, this report does not attempt to be all inclusive. The Office of Water Resources welcomes discussions and participation in studies on additional important topics using this and subsequent reports to provide a sound technical point of departure. Relevant topics for future studies might include current or future water quality issues or their relation to water levels; evaluation of specific impacts of the potential changes in water levels on key natural resources or specific bodies of water; the use of this report's findings by other agencies or programs; and a discussion of state or regional policy issues and the potential uses for the

report's findings for policy modification.

In addition, town water suppliers and planners might want to compare the pumping data in the scenarios with registered and permitted withdrawals as they plan for future water supply needs on the Cape. It is also important to note that the scope of the report is regional, and applies to town or multi-town areas rather than individual bodies of water, except those included in the model. As noted in the report, additional data on other individual bodies of water could provide the basis for a more localized analysis of impacts or more refined scenarios.

NOTE: There are various terms used to describe portions of the Cape, including Outer Cape (generally from Chatham north), Lower Cape (generally parts of eastern Barnstable to Orleans), and mid-Cape (generally Barnstable and west), which are used in describing natural resources in the next section. After that, and based on the USGS terminology used in the model, the rest of this report uses "East Cape", "West Cape" to refer to areas east and west of Yarmouth, as explained in the description of flow cells in Section II. Locally, the Falmouth area is called the "Upper" Cape and Provincetown is called "Lower" or "Outer" Cape.

# I. INVENTORY OF WATER RESOURCES AND USES

## A. Natural Resources

The Cape's rich water resources are used for a variety of non-consumptive uses. Numerous kettlehole ponds left by the retreating glaciers dot the landscape, wetlands and coastal streams provide habitat for fisheries and wildlife, and a wide range of fresh water recreation opportunities exist. The following descriptions and information, furnished by the Massachusetts Division of Fisheries and Wildlife (DFW), provide examples of the kinds of resources on the Cape that may be affected by changes in ground water levels; it is not intended as a comprehensive inventory.

### 1. Fisheries, Wildlife, and Endangered Species

The Massachusetts Division of Fisheries and Wildlife considers coastal plain ponds one of the most unique and sensitive natural communities to occur in the state (Appendix B provides a description of the ponds and their environmental characteristics). These ponds, found primarily in Barnstable and Plymouth counties, occur in glacial kettles lacking surface water inlets or outlets and are therefore hydrologically influenced by precipitation, transpiration, evaporation, and ground water inflows and outflows. The specialized and rare flora that develops on the shores of these ponds is adapted to a particular regime of water level fluctuations which is believed to be strongly influenced by local changes in ground water level. Water withdrawals in the vicinity of these ponds can have dramatic effects on the surface pond levels. Permanent local drawdowns of the ground water table resulting from pumping may ultimately result in a loss of coastal plain pond shore habitat. If the average water level of a pond decreases, the area of shore line habitat also will decrease. Therefore, careful attention should be given to the potential impacts of ground water pumping in the vicinity of these ponds, particularly those priority ponds shown on Table 1.

While the Cape's ponds and coastal streams are spawning and feeding grounds for many native species of fish, the DFW also has stocking programs throughout the Cape. Most coastal streams support natural herring runs. The Quashnet River in Mashpee supports a significant sea-run trout population. The DFW has identified some significant fishery areas on Cape Cod, summarized below.

Outer Cape Cod The Gull Pond/Herring River system supports a "two story" trout fishery. The lower, cooler levels of the pond are stocked with trout; the warmer, upper levels support populations of naturally occurring species including large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners.

The Pamet River supports resident brook trout, migratory brook trout, and stocked trout.

Mid Cape Cod The Stony Brook/Mill Pond/ Walker Pond complex supports a warm water fishery including large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners. The Herring River supports a wild resident brown trout population.

# Table 1

## Coastal Plain Pond Sites in Barnstable County

| Key | SITENAME | BIODIVSIG | LOCALJURIS |
|---|---|---|---|
| S.USMAFO*113 | GRASSY POND DENNIS | B3 | DENNIS |
| S.USMAFO*115 | SIMMONS PONDS | B3 | DENNIS |
| S.USMAFO*116 | CROOKED POND COMPLEX FALMOUTH | B2 | FALMOUTH |
| S.USMAFO*119 | HAWKSNEST POND COMPLEX | B3 | HARWICH |
| S.USMAFO*29 | BAKER POND ORLEANS | B3 | ORLEANS |
| | | | BREWSTER |
| S.USMAFO*36 | MARY DUNN POND COMPLEX | B2 | BARNSTABLE |
| S.USMAFO*64 | SOLS/BLUEBERRY PONDS | B3 | BREWSTER |
| S.USMAFO*70 | WEEKS POND | B3 | SANDWICH |
| S.USMAFO*72 | ELBOW POND COMPLEX | B3 | BREWSTER |
| S.USMAFO*79 | AUNT PATTYS POND | B2 | DENNIS |
| S.USMAFO*86 | OWL/LEES PONDS | B3 | BREWSTER |
| S.USMAHP*1041 | MARES POND/SPECTACLE POND FALMOUTH | B3 | FALMOUTH |
| S.USMAHP*1042 | GRASS POND HARWICH | B3 | HARWICH |
| S.USMAHP*1043 | BLACK POND HARWICH | B3 | HARWICH |
| | | | BREWSTER |
| S.USMAHP*1044 | SHEEP POND BREWSTER | B3 | BREWSTER |
| S.USMAHP*1045 | PONDVIEW ROAD BREWSTER | B3 | BREWSTER |
| S.USMAHP*1046 | LAWRENCE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1047 | TRIANGLE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1048 | SPECTACLE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1049 | SHUBAEL POND | B3 | SANDWICH |
| S.USMAHP*1071 | SNAKE POND | | SANDWICH |
| S.USMAHP*123 | HATHAWAY PONDS | B3 | BARNSTABLE |
| S.USMAHP*163 | DENNIS POND COMPLEX YARMOUTH | B3 | YARMOUTH |
| S.USMAHP*189 | HOG PONDS | B2 | SANDWICH |
| S.USMAHP*34 | SHALLOW POND | B3 | BARNSTABLE |
| S.USMAHP*346 | MUD POND HARWICH/BREWSTER | B3 | HARWICH |
| | | | BREWSTER |
| S.USMAHP*356 | RUN POND | B2 | DENNIS |
| S.USMAHP*359 | HORSE POND COMPLEX | B2 | YARMOUTH |
| S.USMAHP*376 | MINISTER POND | B3 | EASTHAM |
| S.USMAHP*4 | PROVINCETOWN PONDS | B3 | PROVINCETOWN |
| S.USMAHP*410 | TRAILER PARK POND MASHPEE | B4 | MASHPEE |
| S.USMAHP*455 | SCHOOLHOUSE PONDS | B3 | CHATHAM |
| S.USMAHP*490 | LITTLE POND | B3 | BARNSTABLE |
| S.USMAHP*528 | HOXIE POND | B4 | SANDWICH |
| S.USMAHP*543 | MYSTIC LAKE/MIDDLE POND | B4 | BARNSTABLE |
| S.USMAHP*549 | BAKERS POND DENNIS | B4 | DENNIS |
| S.USMAHP*570 | PICTURE LAKE (FLAX POND) | B3 | BOURNE |
| S.USMAHP*581 | GRASSY POND FALMOUTH | B4 | FALMOUTH |
| S.USMAHP*642 | ISLAND POND HARWICH | B3 | HARWICH |
| S.USMAHP*649 | MUDDY POND BARNSTABLE | B3 | BARNSTABLE |
| S.USMAHP*652 | ROBBINS POND | B3 | HARWICH |
| S.USMAHP*67 | GRIFFITHS POND | B4 | BREWSTER |
| S.USMAHP*836 | MILL POND HARWICH | B3 | HARWICH |
| S.USMAHP*84 | BLACK POND/WHITE POND COMPLEX | B3 | CHATHAM |
| S.USMAHP*840 | PERCH POND | B3 | WELLFLEET |
| S.USMAHP*845 | ELISHAS POND | B4 | YARMOUTH |
| S.USMAHP*853 | WASHBURN POND | B3 | MASHPEE |
| S.USMAHP*854 | HAMBLIN POND | B3 | BARNSTABLE |
| S.USMAHP*856 | CEDAR POND | B3 | DENNIS |
| S.USMAHP*862 | UNCLE ISRAELS POND | B3 | ORLEANS |
| S.USMAHP*863 | GOULD POND | B3 | ORLEANS |
| S.USMAHP*936 | CLIFF POND COMPLEX | B2 | BREWSTER |
| S.USMAHP*944 | GREAT POND WELLFLEET COMPLEX | B4 | WELLFLEET |
| S.USMAHP*945 | KINNACUM POND COMPLEX | B3 | WELLFLEET |
| S.USMAHP*949 | GULL POND COMPLEX | B3 | WELLFLEET |
| | | | TRURO |
| S.USMAHP*960 | GOOSE POND | B3 | CHATHAM |
| S.USMAHP*962 | KEELER POND | B4 | BREWSTER |
| S.USMAHP*963 | BUCKS POND COMPLEX | B3 | HARWICH |

Source: Natural Heritage and Endangered Species Program
Massachusetts Division of Fisheries and Wildlife
Data current as of 3 January 1994

Biodiversity Ranks: B1 = Outstanding, B2 = Very High, B3 = High, B4 = Moderate

Seymour Pond supports a warm water fishery including: Large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners.

Long Pond supports a "two story" trout fishery.

Greenland Pond supports a warm water fishery including large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners.

Centerville River/Long Pond/Wequaquet Lake supports a warm water fishery including: Large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners. The Division of Fisheries and Wildlife also stocks this area with northern pike and tiger musker.

Upper Cape Cod The Coonamessett River supports an alewife run, anadromous hatchery trout.

Coonamessett Pond supports a "two story" trout fishery, the warm water layer includes small mouthed bass as well as the species listed above with the exception of large mouthed bass.

Flax Pond supports a warm water fishery including: large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners.

Jenkins Pond supports a stocked trout and resident trout fishery.

Childs River supports native brook trout, anadromous brook trout and stocked brown trout.

Johns Pond supports a "two story" trout fishery, the warm water layer includes small mouthed bass as well as the species listed above.

The Quashnet River supports sea run brown trout, resident wild brook trout, stocked brown trout, and blue-backed herring.

Mashpee River supports wild brook trout, wild brown trout, stocked brown trout, blue-backed herring, sea lamprey, and a rare brook lamprey.

Mashpee Pond/Wakeby Pond complex supports a "two story" trout fishery, the warm water layer includes small mouthed bass as well as the species listed above.

Mill River/Mill Pond/Muddy Pond/Middle Pond/Mystic Lake complex supports a warm water fishery including: large mouthed bass, chain pickerel, sunfish, white perch, yellow perch, brown bullheads, and shiners.

The wetlands, ponds, and streams also provide habitat for waterfowl and fur-bearing animals. Migratory ducks and geese use these areas for feeding and breeding.

## 2. Wetlands

As noted above, the wetlands on Cape Cod provide important wildlife habitat and recreational opportunities. The major wetlands on Cape Cod are shown in Table 2.

**Table 2**
**Wetlands on Cape Cod**

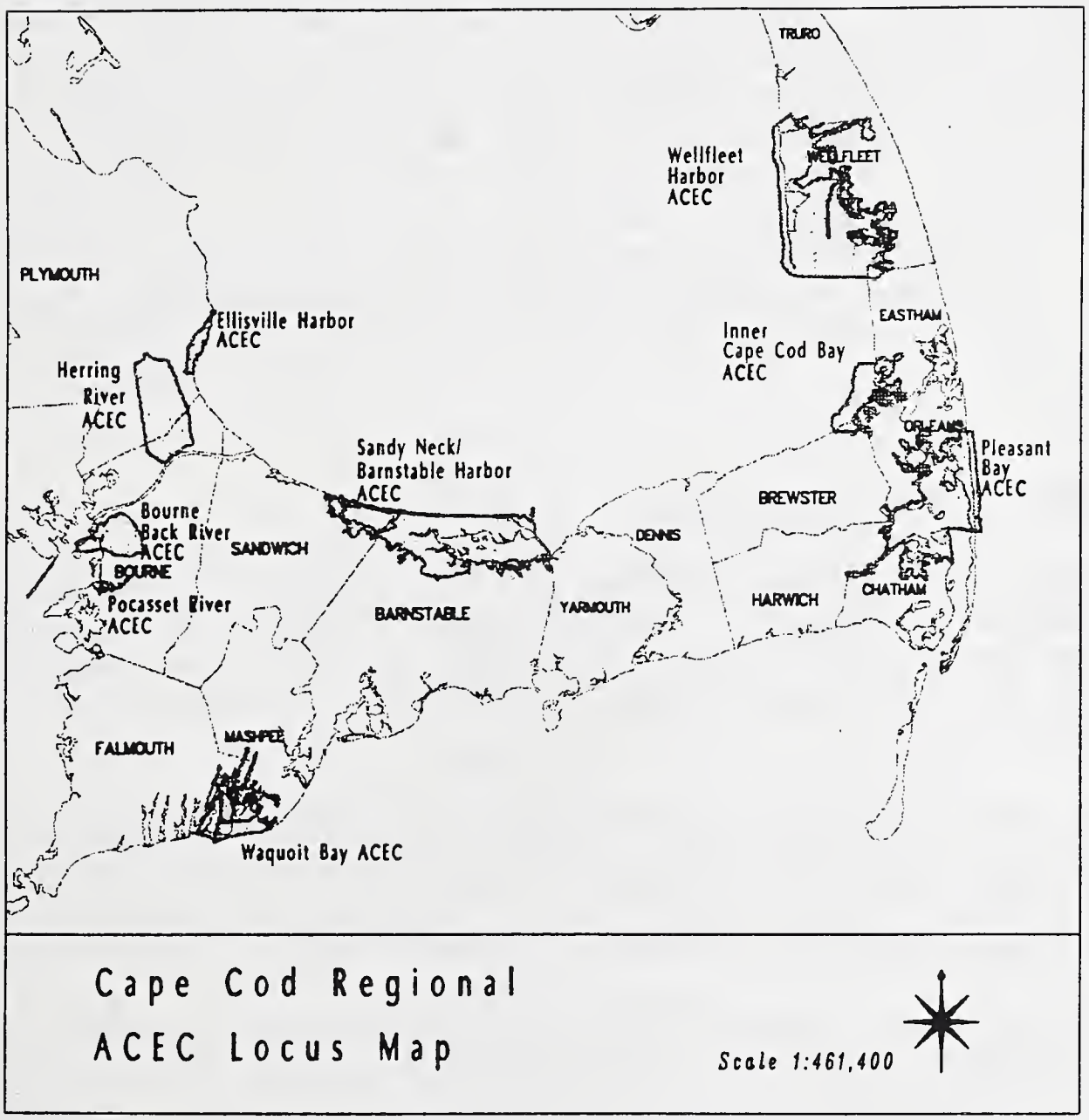
| Wetland name | Location | Acres |
|---|---|---|
| Clapps Pond Wetland | Provincetown | 70 |
| Shank Painter Pond Wetland | Provincetown | 80 |
| Pilgrim Lake Wetland | Truro | 290 |
| Little Pamet Wetland | Truro | 80 |
| Truro River Wetland | Truro | 220 |
| Herring River Wetland | Truro/Wellfleet | 350 |
| Duck Harbor Wetland | Wellfleet | 400 |
| Namskaket Creek Wetland | Brewster/Orleans | 35 |
| Chathamport Wetland | Chatham | 50 |
| Grass Pond Wetland | Harwich | 90 |
| Unnamed Wetland between Orthrop and Sisson Roads | Harwich | 80 |
| Swan Pond River Wetland | Dennis | 140 |
| Ware Creek Wetland | Dennis | 80 |
| Parkers River Wetland | Yarmouth | 80 |
| Witcomb Swamp | Mashpee | 55 |

Source: USDA, Soil Conservation Service 1978

## 3. Areas of Critical Environmental Concern

The Area of Critical Environmental Concern (ACEC) Program was established in 1974 to protect certain resource areas that are of central importance to the welfare, safety, and pleasure of all Massachusetts citizens (MCZM 1989). An ACEC is an area containing concentrations of highly significant environmental resources that has been formally designated by the Commonwealth's Secretary of Environmental Affairs following a public nomination and review process. Between 1975 and 1993, the Secretary designated 22 ACECs encompassing approximately 155,000 acres. Designation of an area as an ACEC provides a higher level of environmental review for proposed activities. The seven designated ACECs on Cape Cod are: Bourne Back River, Pocasset River, Waquoit Bay, Sandy Neck, Pleasant Bay, Inner Cape Cod Bay, and Wellfleet Harbor (Figure 3). A full description of the program and designated areas can be found in *ACEC Program Guide* (DEM 1993).

Figure 3




Source: DEM 1993

## B. Human Use

### 1. Public Water Supply Systems

Public water supply system customers are the primary water users on Cape Cod, with a base off-season average day demand (ADD) of 18.68 million gallons per day (mgd) and an in-season average day demand of 38.73 mgd. All but two communities are served totally or in part by a public water supply system. There are 18 separate water supply systems serving Cape Cod (Appendix C). The town of Barnstable has four public water supply systems: the Barnstable Water Company, the Barnstable Fire District, the Centerville-Osterville-Marston's Mills (COMM) Fire District, and the Cotuit Fire District. Bourne, south of the Cape Cod Canal, has two public water suppliers: the Bourne Water District and the South Sagamore Water District, as well as the Otis Air National Guard (ANG) Base. There are two other water districts located in Bourne, north of the Cape Cod Canal, the North Sagamore Water District and the Buzzards Bay Water Districts. These derive all their water from the Buzzards Bay basin and will be discussed in that basin plan. Falmouth is the only study area community served by a surface water source, Long Pond Reservoir. The town also has one ground water source, Fresh Pond well. Ground water is the source of all other public water supplies.

### 2. Demographic Profile of Cape Cod

The 1990 federal census population of Cape Cod was 186,605. This includes only year-round (off-season) population. Seasonal population will be discussed below. Barnstable is the most populous community in the study area, with a 1990 population of 41,949, or 22 percent of the Cape's total population. Truro has the smallest year-round population, 1,573.

Of the 186,605 persons living year-round in the basin during 1990, 154,252 people, or 83 percent, obtain their water from a public water supply system. Three of the 15 basin communities are 100 percent served by a public water supply system. Table 3 shows the off-season service population of Cape Cod water suppliers in 1990.

The 1990 off-season service population represents that portion of the population that is served by the community's central water supply system(s). If a community's 1990 off-season service population is 90 percent, it means that 90 percent of the population is on a central supply system, and the other 10 percent of the population is self-supplied, relying entirely on individual private wells.

**Seasonal Population** Cape Cod has long been a summer resort attracting visitors from all over the country. Sandy beaches, water-related recreation activities, and other natural amenities lure day visitors and part-time residents to the Cape in large numbers, swelling the year-round population by 175 percent. The seasonal influx begins in June, peaks in July and tapers off by Labor Day, in early September. However, local officials have noted that the season has been starting earlier and extending later in recent years. Many

**Table 3**
**Off-Season Service Population**

| Community | 1990 Federal Census | Percent Service Population | Out of Town Population | Base Service Population |
|---|---|---|---|---|
| Barnstable | 40,949 | | | |
| Barnstable FD | | 8% | | 3,276 |
| Barnstable WC | | 26% | | 10,647 |
| COMM FD | | 56% | | 22,931 |
| Cotuit FD | | 5% | | 2,047 |
| Bourne[1] | 16,064 | | | |
| S. Sagamore WD | | 5% | | 803 |
| Bourne WD | | 49% | | 7,871 |
| Brewster | 8,440 | 92% | | 7,765 |
| Chatham | 6,579 | 70% | | 4,605 |
| Dennis | 13,864 | 95% | | 13,171 |
| Eastham | 4,462 | | | |
| Falmouth | 27,960 | 85% | | 23,766 |
| Harwich | 10,275 | 82% | 25 | 8,451 |
| Mashpee WD | 7,884 | 48% | | 3,784 |
| Orleans | 5,838 | 94% | 106 | 5,594 |
| Provincetown | 3,561 | 100% | 400 | 3,961 |
| Sandwich | 15,489 | 75% | | 11,617 |
| Truro | 1,573 | | | |
| Wellfleet | 2,493 | | | |
| Yarmouth | 21,174 | 99% | | 20,962 |
| TOTALS | 186,605 | | | 154,252 |

DEM Office of Water Resources

[1] The year-round population of Otis Air National Guard Base is included in the federal census for Bourne.

individuals who own second homes on Cape Cod begin spending weekends at their homes in early May and continue weekend visits through Columbus Day in mid-October. Whereas the Cape's year-round population is 186,605, its summer population is estimated at over 514,000. Table 4 shows the year-round and summer changes in population for each study area community.

**In-Season Service Population** The in-season service population (those served by public water supply systems) increases by about 185 percent over the off-season service population. The off-season service population of 154,252 swells to 438,790 during the summer. This figure is derived by adding the estimated summer population to the base off-season service population. The in-season service population does not include "day-trippers" who visit the Cape, but do not stay overnight. Table 5 shows the in-season service population for Cape Cod water suppliers.

The summer population was estimated by local water superintendents and town clerks, or their consultants. Various methods were used to arrive at the estimate, such as multiplying the number of water services by 2.8 people or the number of bedrooms by 2 people per bedroom. To further refine the summer population figures, OWR used the summer population estimates which had been developed by CCC, for 1980 and 1990. OWR took the growth rate for this time period and compared it with the information provided by local officials.

**Population Projections** The Massachusetts Institute for Social and Economic Research estimates that the year-round population of Cape Cod will increase from the 1990 federal census of 186,605 to 229,437 in 2020, an increase of 23 percent.

Summer population is expected to rise from the estimated 1990 summer population of 512,520 people to 594,831 people by 2020, an increase of 16 percent. These summer population figures include both year-round and seasonal residents. Tables 6 and 7 show the year-round and summer population projections from 1990 to 2020 for the basin communities.

**Projected Service Area Expansion** In those communities where less than 100 percent of population is served, estimates of service area growth were developed from information obtained from local water supply system managers and from historical data relating to the way service areas develop in response to, or in anticipation of, population growth within a community. Unless a community has specifically indicated a difference in its expected service population growth, it is assumed, for planning purposes that:

1. Those communities with a 100 percent service population in 1990 will remain at 100 percent through the planning period.
2. Those communities with a 1990 service population of 90 percent or more will increase 5 percent a decade.
3. Those communities with a service population of less than 90 percent are adjusted on an individual basis, as reported by the water system managers.

Table 8 illustrates how these communities are expected to increase the percentage of the population served during the 1989-2020 study period.

**Table 4**
**Comparason of Total Year Round and Summer Populations**

| Community | 1990 Federal Census (Year round) | Estimated Total Summer Population |
|---|---|---|
| Barnstable | 40,949 | 81,898 |
| Bourne[1] | 16,064 | 24,214 |
| Brewster | 8,440 | 29,118 |
| Chatham | 6,579 | 21,448 |
| Dennis | 13,864 | 54,624 |
| Eastham | 4,462 | 21,016 |
| Falmouth | 27,960 | 69,900 |
| Harwich | 10,275 | 26,612 |
| Mashpee | 7,884 | 27,988 |
| Orleans | 5,838 | 17,850 |
| Provincetown | 3,561 | 18,482 |
| Sandwich | 15,489 | 34,850 |
| Truro | 1,573 | 13,009 |
| Wellfleet | 2,493 | 15,880 |
| Yarmouth | 21,174 | 57,170 |
| TOTAL | 186,605 | 514,059 |

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[1] The population of Otis Air National Guard Base is included in the figures for Bourne.

**Table 5**
**In-Season Service Population**

| Community | 1990 Federal Census (Year Round) | Percent Service Population | Out of Town Population | In-Season Population Increase | In-Season Service Population |
|---|---|---|---|---|---|
| Barnstable | 40,949 | | | | |
| Barnstable FD | | 8% | | 1,000 | 4,276 |
| Barnstable WC | | 26% | | 12,000 | 22,647 |
| COMM FD | | 56% | | 21,210 | 44,141 |
| Cotuit FD | | 5% | | 2,200 | 4,247 |
| Bourne[1] | 16,064 | | | | |
| S. Sagamore WD | | 5% | | 150 | 953 |
| Bourne WD | | 49% | | 8,000 | 15,871 |
| Brewster | 8,440 | 92% | | 20,678 | 28,443 |
| Chatham | 6,579 | 70% | | 14,869 | 19,474 |
| Dennis | 13,864 | 95% | | 40,760 | 53,931 |
| Eastham | 4,462 | | | 16,554 | |
| Falmouth | 27,960 | 85% | | 41,940 | 65,706 |
| Harwich | 10,275 | 82% | 25 | 16,337 | 24,788 |
| Mashpee WD | 7,884 | 48% | | 20,104 | 23,888 |
| Orleans | 5,838 | 94% | 106 | 12,012 | 17,606 |
| Provincetown | 3,561 | 100% | 400 | 14,921 | 18,882 |
| Sandwich | 15,489 | 75% | | 19,361 | 30,978 |
| Truro | 1,573 | | | 11,436 | |
| Wellfleet | 2,493 | | | 13,387 | |
| Yarmouth | 21,174 | 99% | | 35,996 | 56,958 |
| TOTALS | 189,605 | | | 325,915 | 438,790 |

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[1] The population of Otis Air National Guard Base is included in the federal census for Bourne.

**Table 6**
**Year Round Population Projections**

| Community | 1990 Federal Census (Year Round) | 1995 | 1995 | 2010 | 2020 |
|---|---|---|---|---|---|
| Barnstable | 40,949 | 42,684 | 45,370 | 45,643 | 50,104 |
| Bourne[1] | 16,064 | 16,625 | 17,577 | 17,898 | 19,642 |
| Brewster | 8,440 | 9,096 | 9,955 | 9,550 | 10,585 |
| Chatham | 6,579 | 6,724 | 7,019 | 7,205 | 7,819 |
| Dennis | 13,864 | 14,196 | 14,844 | 15,583 | 17,197 |
| Eastham | 4,462 | 4,715 | 5,067 | 5,026 | 5,554 |
| Falmouth | 27,960 | 28,761 | 30,204 | 30,974 | 33,867 |
| Harwich | 10,275 | 10,460 | 10,878 | 11,382 | 12,444 |
| Mashpee | 7,884 | 9,244 | 10,810 | 10,850 | 10,900 |
| Orleans | 5,838 | 5,987 | 6,269 | 6,465 | 7,067 |
| Provincetown | 3,561 | 3,451 | 3,424 | 3,497 | 3,505 |
| Sandwich | 15,489 | 16,506 | 17,892 | 17,552 | 19,471 |
| Truro | 1,573 | 1,625 | 1,713 | 1,711 | 1,848 |
| Wellfleet | 2,493 | 2,578 | 2,721 | 2,717 | 2,940 |
| Yarmouth | 21,174 | 21,691 | 22,692 | 23,926 | 26,494 |
| TOTAL | 186,605 | 194,343 | 206,435 | 209,979 | 229,437 |

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[1] The year-round population of Otis Air National Guard Base is included in the federal census for Bourne.

**Table 7**
**Estimated Summer Population Projections**

| Community | 1990 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Barnstable | 81,898 | 79,094 | 81,780 | 82,053 | 86,514 |
| Bourne[1] | 24,214 | 24,775 | 25,727 | 26,048 | 27,792 |
| Brewster | 29,118 | 29,835 | 31,956 | 31,611 | 35,036 |
| Chatham | 21,448 | 21,450 | 21,899 | 22,984 | 24,943 |
| Dennis | 54,624 | 51,815 | 50,470 | 57,034 | 62,941 |
| Eastham | 21,016 | 21,783 | 23,612 | 23,421 | 25,882 |
| Falmouth | 69,900 | 69,314 | 71,583 | 75,267 | 82,297 |
| Harwich | 26,612 | 27,091 | 28,199 | 29,504 | 32,255 |
| Mashpee | 27,988 | 29,026 | 31,673 | 34,829 | 34,989 |
| Orleans | 17,850 | 18,207 | 18,677 | 19,048 | 18,198 |
| Provincetown | 18,482 | 18,049 | 18,034 | 18,549 | 18,591 |
| Sandwich | 34,850 | 34,498 | 34,889 | 36,859 | 40,889 |
| Truro | 13,009 | 13,471 | 13,635 | 13,979 | 15,098 |
| Wellfleet | 15,880 | 16,113 | 16,516 | 16,927 | 18,316 |
| Yarmouth | 57,170 | 55,312 | 55,822 | 61,490 | 68,090 |
| TOTAL | 514,059 | 509,833 | 524,472 | 549,603 | 591,831 |

DEM Office of Water Resources

[1] The year-round population of Otis Air National Guard Base is included in the federal census for Bourne.

Summer population figures were based on estimates by communities and the Cape Cod Commission.

**Table 8**
**Percent of Population Served**

| Community | 1989 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Barnstable | 95 | 95 | 99 | 99 | 99 |
| Bourne* | 54 | 56 | 64 | 64 | 64 |
| Chatham | 70 | 100 | 100 | 100 | 100 |
| Dennis | 95 | 95 | 100 | 100 | 100 |
| Eastham | 0 | 0 | 0 | 0 | 0 |
| Falmouth | 85 | 90 | 95 | 100 | 100 |
| Harwich | 82 | 85 | 90 | 90 | 95 |
| Mashpee | 40 | 48 | 63 | 68 | 73 |
| Orleans | 94 | 94 | 94 | 95 | 95 |
| Provincetown | 100 | 100 | 100 | 100 | 100 |
| Sandwich | 75 | 80 | 90 | 95 | 95 |
| Truro | 0 | 0 | 0 | 0 | 0 |
| Wellfleet | 0 | 0 | 0 | 0 | 0 |
| Otis ANG** | 100 | 100 | 100 | 100 | 100 |
| Yarmouth | 99 | 99 | 99 | 99 | 99 |

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* Portion south of Cape Cod Canal only
** Refers to ANG Population only; not a percent of town population

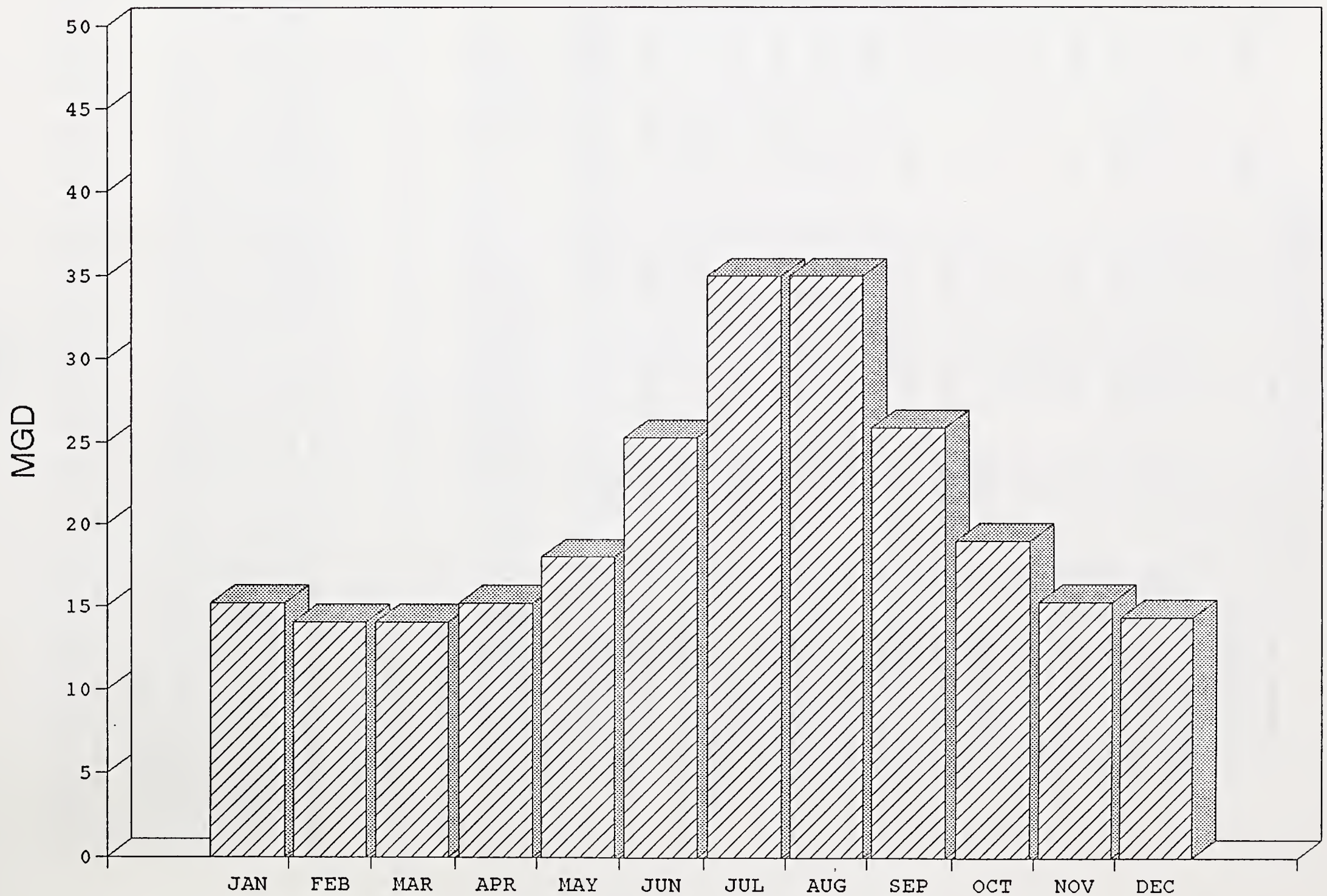
3. Current Water Use

Cape Cod is the premier summer resort in Massachusetts and experiences an increase of summer residents that is nearly three times the off-season population. Public water suppliers are called on to supply twice as much water in the summer months (June, July, August) as is needed during the off-season months. Because of these distinct demand periods, OWR has modified its demand methodology to forecast water needs for both seasonal and off-season months. (See Section 4 for water needs forecasts and Appendix A for methodology.)

Figure 4 displays the total 1990 monthly average day demands for the study area. The highest monthly ADD was in July when 34.98 mgd was used. The lowest monthly ADD was

# MONTHLY WATER USE 1990
# CAPE COD BASIN

Figure 4



14.03 mgd in February. The summer water demand occurs from June through August. Off-season demand occurs from January to May and September to December.

Falmouth and Yarmouth have the largest water supply systems, with off-season base average day demands of 2.83 mgd and 2.72 mgd, and seasonal base average day demands of 5.23 mgd and 5.79 mgd, respectively. The COMM Fire District in Barnstable and the Mashpee Water District experience the largest percentage increases in water use from off-season to summer, (256 percent and 295 percent respectively). Tables 9 and 10 show the off-season and in-season average day demands for the 1986 to 1990 time period.

**Table 9**
**Off-Season Water Demand**

| Community | 1986 | 1987 | 1988 | 1989 | 1990 | AVERAGE |
|---|---|---|---|---|---|---|
| Barnstable WC | 2.33 | 2.37 | 2.47 | 2.42 | 2.50 | 2.42 |
| Barnstable FD | 0.34 | 0.37 | 0.35 | 0.33 | 0.30 | 0.34 |
| Cotuit FD | 0.27 | 0.31 | 0.28 | 0.29 | 0.33 | 0.30 |
| Comm FD | 1.68 | 1.95 | 1.95 | 1.96 | 1.83 | 1.87 |
| S. Sagamore WD | 0.07 | 0.09 | 0.09 | 0.09 | 0.08 | 0.08 |
| Bourne WD | 0.64 | 0.72 | 0.79 | 0.74 | 0.75 | 0.73 |
| Brewster | 0.69 | 0.74 | 0.81 | 0.86 | 0.89 | 0.80 |
| Chatham | 0.54 | 0.59 | 0.62 | 0.65 | 0.73 | 0.63 |
| Dennis | 1.79 | 1.83 | 1.83 | 1.85 | 1.91 | 1.84 |
| Falmouth | 2.63 | 2.86 | 2.81 | 2.84 | 3.00 | 2.83 |
| Harwich | 0.97 | 1.16 | 1.22 | 1.20 | 1.31 | 1.17 |
| Mashpee WD | 0.12 | 0.16 | 0.21 | 0.20 | 0.25 | 0.19 |
| Orleans | 0.74 | 0.73 | 0.79 | 0.78 | 0.73 | 0.75 |
| Provincetown | 0.64 | 0.65 | 0.61 | 0.63 | 0.61 | 0.63 |
| Sandwich | 0.80 | 0.92 | 1.01 | 0.99 | 1.13 | 0.97 |
| Yarmouth | 2.60 | 2.71 | 2.85 | 2.80 | 2.62 | 2.72 |
| Otis ANG | 0.44 | 0.39 | 0.36 | 0.39 | 0.36 | 0.39 |
| TOTAL | 17.29 | 18.55 | 19.05 | 19.02 | 19.33 | 18.65 |

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**Table 10**
**In-Season Water Demand**

| Community | 1986 | 1987 | 1988 | 1989 | 1990 | Average |
|---|---|---|---|---|---|---|
| Barnstable WC | 3.82 | 4.63 | 4.50 | 4.29 | 3.78 | 4.20 |
| Barnstable FD | 0.53 | 0.82 | 0.76 | 0.72 | 0.57 | 0.68 |
| Cotuit FD | 0.53 | 0.77 | 0.72 | 0.68 | 0.65 | 0.67 |
| COMM FD | 3.44 | 5.60 | 5.37 | 5.10 | 4.40 | 4.78 |
| S. Sagamore WD | 0.13 | 0.16 | 0.16 | 0.15 | 0.15 | 0.15 |
| Bourne WD | 1.11 | 1.66 | 1.70 | 1.24 | 1.39 | 1.42 |
| Brewster | 1.17 | 1.17 | 1.73 | 1.62 | 1.69 | 1.48 |
| Chatham | 1.00 | 1.41 | 1.42 | 1.37 | 1.30 | 1.30 |
| Dennis | 3.90 | 5.05 | 4.74 | 4.65 | 4.13 | 4.49 |
| Falmouth | 4.24 | 5.69 | 5.41 | 5.32 | 5.49 | 5.23 |
| Harwich | 2.07 | 3.27 | 3.14 | 3.05 | 2.78 | 2.86 |
| Mashpee WD | 0.37 | 0.56 | 0.67 | 0.61 | 0.63 | 0.57 |
| Orleans | 1.30 | 1.74 | 1.58 | 1.62 | 1.35 | 1.52 |
| Provincetown | 1.35 | 1.48 | 1.19 | 1.39 | 1.21 | 1.32 |
| Sandwich | 1.18 | 1.83 | 1.86 | 1.74 | 1.74 | 1.67 |
| Yarmouth | 4.85 | 6.32 | 6.45 | 6.15 | 5.20 | 5.79 |
| Otis ANG | 0.50 | 0.66 | 0.56 | 0.57 | 0.45 | 0.55 |
| TOTAL | 31.49 | 42.82 | 41.96 | 40.27 | 36.91 | 38.69 |

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Water demand figures were obtained from the "Water Supply Statistics Report" submitted by each water supply agency to the regional offices of the Division of Water Supply in the Department of Environmental Protection (DEP). The average day demands for each year were calculated by dividing the year's water consumption (in gallons) by 365 days (366 in leap years).

Cape Cod has a distinct summer season and off-season in terms of water use. Off-season demand was calculated using January through May and September through December; seasonal demand was calculated using June, July and August demands. However, for the requirements of the Water Management Act only, OWR weighted the summer demand by 5 and the winter by 7 to derive the single annual number needed for applications to DEP

for withdrawal permits. Summer and off-season ADD were calculated by dividing the water consumption for each month by the number of days in that month. The total for the months in each season was then averaged by the number of months in the season's period.

4. Water Needs Forecasts: Average Day Demand

The average day demand (ADD) is the total amount of water used by a community during the year, divided by 365 days (366 in a leap year). Because the amount of water used varies significantly from season to season, the average figure does not reflect the actual amount of variation.

The demographic character of Cape Cod changes dramatically from the off-season to the summer months. The influx of summer residents and visitors to Cape Cod communities places heavy demands on public water supply systems. Using traditional methods to predict future water use minimizes the differences between the seasons. Peak demand is underestimated for the summer months and average demand is overestimated for the off-season months. Therefore, OWR, after consultation with water superintendents in the Cape Cod communities, The Cape Cod Commission, and the Association of for the Preservation of Cape Cod, has decided to project water use separately for these two time periods. The off-season months are January through May and September through December. Summer months are June through August. Projections of demand combined with an assessment of available supplies can assist communities in planning the direction of their future development.

In reviewing the trends of water needs for many Massachusetts communities, OWR has found that basing future demand projections on a long historical trend of water use gives incorrectly low results in those communities where population, employment, and water use have changed recently. Conversely, using only the most recent year's water demand figures may be inaccurate due to onetime events requiring large quantities of water, such as a large fire, or a particularly warm or dry summer. To modify these influences and still reflect a reasonable trend, OWR has used the average day demand for the years 1986-1990, termed the "base demand" for each community, as the basis for projections. In slower growing communities, the five year average is similar to the long term trend.

Cape Cod has an off-season base demand and an in-season base demand. The off-season base demand is 18.68 mgd. This is the average of the off-season ADD for 1986 through 1990. By 2020, the off-season ADD is projected to reach 27.76 mgd. In-season base ADD is 38.73 mgd. This is the average in-season ADD for 1986 through 1990. By 2020, in-season ADD is projected to reach 54.38 mgd. Table 11 lists the projected off-season and in-season average day demands from 1995 to 2020.

5. Water Management Act Permitting Program on Cape Cod

The Massachusetts Water Management Act (WMA) (MGL C. 21G) and regulations (310 CMR 36.00) became effective in March 1986. The act calls for comprehensive management, by river basin, of the Commonwealth's surface and ground water resources in order to ensure an adequate supply of water for all citizens now and in the future.

## Table 11
## Off-Season and In-Season Water Needs Forecasts

| Community | BASE | | 1995 | | 2000 | | 2010 | | 2020 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Off-Season | In-Season | Off-Season | In-Season | Off-Season | In-Season | Off-Season | In-Season | Off-Season | In-Season |
| Barnstable | | | | | | | | | | |
| Barnstable FD | 0.34 | 0.68 | 0.38 | 0.75 | 0.43 | 0.84 | 0.46 | 0.94 | 0.52 | 1.00 |
| Barnstable WC | 2.42 | 4.20 | 2.51 | 4.29 | 2.65 | 4.43 | 2.67 | 4.48 | 2.89 | 4.66 |
| COMM | 1.87 | 4.78 | 2.10 | 5.10 | 2.24 | 5.31 | 2.27 | 5.38 | 2.50 | 5.67 |
| Cotuit FD | 0.30 | 0.67 | 0.31 | 0.68 | 0.32 | 0.69 | 0.32 | 0.70 | 0.34 | 0.72 |
| Bourne | | | | | | | | | | |
| S. Sagamore WD | 0.08 | 0.15 | 0.08 | 0.15 | 0.09 | 0.16 | 0.09 | 0.16 | 0.10 | 0.17 |
| Bourne WD | 0.73 | 1.42 | 0.81 | 1.53 | 1.02 | 1.76 | 1.06 | 1.87 | 1.19 | 1.97 |
| Brewster | 0.80 | 1.48 | 0.95 | 1.65 | 1.15 | 1.90 | 1.17 | 2.12 | 1.35 | 2.29 |
| Chatham | 0.63 | 1.30 | 0.82 | 1.47 | 0.84 | 1.51 | 0.86 | 1.60 | 0.91 | 1.76 |
| Dennis | 1.84 | 4.49 | 1.84 | 4.16 | 2.05 | 4.16 | 2.17 | 4.79 | 2.40 | 5.26 |
| Falmouth | 2.83 | 5.23 | 3.00 | 5.29 | 3.22 | 5.58 | 3.41 | 5.58 | 3.64 | 6.56 |
| Harwich | 1.17 | 2.86 | 1.22 | 2.95 | 1.32 | 3.12 | 1.37 | 3.27 | 1.52 | 3.56 |
| Mashpee WD | 0.21 | 0.62 | 0.33 | 1.77 | 0.51 | 2.03 | 0.56 | 2.33 | 0.61 | 2.38 |
| Orleans | 0.75 | 1.52 | 0.91 | 1.83 | 1.12 | 2.20 | 1.32 | 2.91 | 1.55 | 2.83 |
| Provincetown | 0.63 | 1.32 | 0.62 | 1.29 | 0.65 | 1.28 | 0.66 | 1.33 | 0.66 | 1.33 |
| Sandwich | 0.97 | 1.67 | 1.18 | 1.83 | 1.53 | 2.12 | 1.69 | 2.69 | 1.95 | 2.87 |
| Yarmouth | 2.72 | 5.79 | 3.22 | 6.53 | 3.82 | 7.58 | 4.44 | 10.14 | 5.24 | 10.80 |
| Otis ANG | 0.39 | 0.55 | 0.39 | 0.55 | 0.39 | 0.55 | 0.39 | 0.55 | 0.39 | 0.55 |
| TOTAL | 18.68 | 38.73 | 20.67 | 41.82 | 23.35 | 45.22 | 24.91 | 50.84 | 27.76 | 54.38 |

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The act authorizes the Department of Environmental Protection (DEP) to regulate and monitor significant water withdrawals from Massachusetts ground and surface water supplies and gives DEP greater authority to manage water supply emergencies. Implementation of the act has taken place in two phases: registration of the volume of withdrawals from existing sources and permitting of the volume of water withdrawals from new sources.

**Registered** volumes refer to the average amount of water withdrawn from a community's sources between 1981 and 1985. All those who withdrew more than an average of 100,000 gallons per day during the 1981-1985 period were required to register those withdrawals by January 4, 1988.

**Permitted** volumes reflect withdrawals from new sources over 100,000 gallons per day or withdrawals from registered sources above the volumes previously registered. Permits are issued for periods of 20 years with a five-year interim review.

Because the WMA only permits for average annual volumes withdrawn, it was necessary to develop average annual forecasts for use in the permitting process. In order to reflect the seasonal variation in water needs on Cape Cod, OWR took a weighted average of the in-season and off-season forecasts shown in Table 11. The equation used to determine the annual water needs forecasts is:

$$\text{Annual Water Needs} = [(\text{off-season demand} \times 7) + (\text{in-season demand} \times 5)] \div 12$$

The resulting average annual water needs forecasts (Table 12) were approved by the Water Resources Commission in December 1991 and were used by DEP in the permitting process.

In October 1992, the Water Resources Commission adopted revised water conservation standards (WRC 1992) for the Commonwealth which were adapted for the water withdrawal permitting program at DEP. Each permit to withdraw water includes conditions requiring conservation measures to be adopted by the permit holder. Table 13 shows the recent status of conservation efforts by Cape water suppliers.

Permitting and registration are being carried out by river basin, according to the regulations. Public water suppliers with sources in more than one basin will register their sources in each basin and will apply for permits as the basins are scheduled for permitting. After all permit applications have been submitted for a basin, applications for additional withdrawals can be submitted on the filing date for the basin in subsequent years.

**Table 12**
**1995 - 2020 Average Annual Water Needs Forecasts**
**(million gallons per day)**

| Community | W.M.A. Registration | Base 1986-90 ADD | 1995 | 2000 | 2010 | 2020 | Change Base-2020 |
|---|---|---|---|---|---|---|---|
| Barnstable | | | | | | | |
| Barnstable FD | 0.34 | 0.41 | 0.53 | 0.60 | 0.66 | 0.72 | 0.31 |
| Barnstable WC | 2.71 | 2.85 | 3.25 | 3.39 | 3.42 | 3.63 | 0.78 |
| Comm FD | 1.98 | 2.57 | 3.35 | 3.52 | 3.57 | 3.82 | 1.25 |
| Cotuit FD | 0.27 | 0.38 | 0.46 | 0.47 | 0.48 | 0.50 | 0.12 |
| Bourne | | | | | | | |
| Bourne WD | 0.73 | 0.90 | 1.11 | 1.33 | 1.40 | 1.52 | 0.62 |
| S. Sagamore WD | 0.09 | 0.10 | 0.11 | 0.12 | 0.12 | 0.13 | 0.03 |
| Brewster | 0.63 | 1.03 | 1.24 | 1.46 | 1.57 | 1.74 | 0.71 |
| Chatham | 0.70 | 0.80 | 1.09 | 1.12 | 1.17 | 1.26 | 0.46 |
| Dennis | 2.10 | 2.49 | 2.81 | 2.93 | 3.26 | 3.59 | 1.10 |
| Falmouth | 2.95 | 3.41 | 3.95 | 4.20 | 4.31 | 4.86 | 1.45 |
| Harwich | 1.20 | 1.58 | 1.94 | 2.07 | 2.16 | 2.37 | 0.79 |
| Mashpee | 0.14 | 0.45 | 0.93 | 1.14 | 1.30 | 1.35 | 0.90 |
| Orleans | 0.86 | 0.94 | 1.29 | 1.57 | 1.98 | 2.08 | 1.14 |
| Provincetown | 1.25 | 0.79 | 0.90 | 0.91 | 0.94 | 0.94 | 0.15 |
| Sandwich | 0.77 | 1.14 | 1.45 | 1.78 | 2.11 | 2.33 | 1.19 |
| Yarmouth | 3.03 | 3.47 | 4.60 | 5.39 | 6.82 | 7.56 | 4.09 |
| Otis ANG | 0.54 | 0.43 | 0.46 | 0.46 | 0.46 | 0.46 | 0.03 |
| TOTAL | 20.29 | 23.74 | 26.09 | 29.09 | 35.73 | 38.86 | 15.12 |

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## Table 13
## Water Conservation Status

| Community | % Unc. Water | Pub. Ed. | Leak Det. | Metering | | | Pricing | | Residential Use | | Public Use | | Supply Management | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | % meter | Reg. Test. | Times Read* | Rate Struct. | Full Cost | Retro. Devic. | Plumb. Code | Retro. Devic. | Plumb. Code | Emerg. Plan** | Water Audit | Cons. Plan |
| Barnstable | | | | | | | | | | | | | | | |
| Barnstable FD | 4 | yes | annual | 100 | yes | 2/y;4/y | incr. | yes | yes | yes | no | yes | yes | yes | yes |
| Barnstable WC | 20 | yes | (1) | 81 | yes | 4/y;1/m | decr. | yes | (2) | yes | (4) | yes | no | yes | yes |
| COMM FD | 9 | yes | 2 yrs | 100 | yes | 2/y | incr. | yes | (3) | yes | (5) | yes | yes | yes | yes |
| Cotuit FD | 16 | yes | 2 yrs | 100 | yes | 1/y | incr. | yes | (3) | yes | na(6) | yes | yes | yes | yes |
| Bourne | | | | | | | | | | | | | | | |
| S. Sagamore WD | (0) | yes | survey | 100 | yes | 1/y | incr. | no | (3) | yes | (3) | yes | yes | no | no |
| Bourne WD | 8 | yes | 3 yrs | 100 | yes | 2/y | flat | yes | (3) | yes | (0) | yes | yes | yes | yes |
| Brewster | 8 | yes | no (7) | 100 | yes | 2/y | flat | yes | yes | yes | no | yes | yes | yes | yes |
| Chatham | 23 | yes | 5 yrs | 100 | yes | 4/y | incr. | yes | (3) | (8) | no | (8) | yes | yes | yes |
| Dennis | 10 | yes | ongoing | 100 | yes | 2/y | incr. | yes | no | yes | yes | yes | no | no | yes |
| Falmouth | 20(0) | yes | survey | 100 | yes | 2/y | incr. | yes | yes | yes | yes | yes | yes | yes | yes |
| Harwich | 11.5 | yes | ongoing | 100 | yes | 2/y | incr. | (9) | yes | yes | yes | yes | yes | yes | yes |
| Mashpee WD | 6% | yes | 5 yrs | 100 | yes | 2/y | incr. | yes | (3) | yes | no | yes | yes | yes | yes |
| Orleans | 17.5 | yes | 5 yrs | 100 | yes | 2/y | incr. | no | no | yes | no | yes | no | yes | yes |
| Provincetown | 14-20 | yes | 5 yrs | 100 | yes | 2/y | incr. | yes | yes | (8) | yes | (8) | no | no | yes |
| Sandwich | 4.2 | yes | ongoing | 100 | yes | 2/y | incr. | yes | (3) | yes | yes | yes | yes | yes | yes |
| Yarmouth | 22 | yes | ongoing | 100 | yes | 1/y | incr. | yes | no | yes | no | yes | yes | yes | yes |

DEM Office of Water Resources

* Where two time periods are given, first indicates smaller customers; second indicates large or commercial meters;
** If no, water supplier has informal agreements with neighboring communities to assist during water supply emergencies
(1) Leak detection program began 10/18/93; frequency of future leak detection surveys will depend on results
(2) Have devices available for distribution, but haven't started program
(3) Cooperative program with the Cape and Islands Self-Reliance Corp. or the Barnstable County Water Utilities Association
(4) Town plumbing inspector has been installing in town buildings
(5) COMM Fire District does not serve entire town of Barnstable; retrofit devices installed in all public buildings within the District
(6) There are no public buildings within the Cotuit Fire District
(7) System is less than 20 years old; planning on instituting formal program in 5-7 years.
(8) The Board of Health or Building/Plumbing Inspector is responsible for enforcing plumbing code
(9) Covers all but bond payments
(0) Not able to update

## 6. Wastewater Treatment

On-site septic systems and subsurface injection of treated municipal sewage return water to the aquifer. This type of wastewater treatment is used because the Massachusetts Ocean Sanctuaries Act (M.G.L. c. 132A §13-16, 18) prohibits any new discharge of municipal wastes into the Ocean Sanctuaries surrounding Cape Cod (the Cape Cod Ocean Sanctuary, the Cape and Islands Oceans Sanctuary, and the Cape Cod Bay Ocean Sanctuary (Figure 5). Subsurface injection of wastewater also serves to replenish the water levels of the aquifer. However, because of the highly permeable nature of Cape soils, the aquifer is susceptible to contamination from septic wastes and other sources. Nitrogen from septic systems and municipal sewage systems, as well as from fertilizer leachate, have caused increased levels of nitrate in ground water. Water supplies have also been threatened by naturally occurring substances such as iron, manganese, hydrogen sulfide and seawater. There also have been incidences of water supply contamination from road salt, leaky underground storage tanks, and landfills. (CCPEDC 1978, LeBlanc et. al. 1986, and Special Legislative Commission on Water Supply 1986).

## 7. Industrial, Commercial and Agricultural Water Supplies

Two industrial and commercial users located on Cape Cod are registered under the WMA. Estimated water needs in this category is 0.91 mgd per year.

Cranberry cultivation and processing are an important part of the economy on Cape Cod. There are over 1,156 acres of cranberry bogs on the Cape. Cranberry cultivation is a water-intensive process. Bogs are flooded throughout the year. In winter, flooding prevents desiccation or "winterkilling"; in the spring and fall, bogs are flooded to prevent frost damage. Bogs may also be flooded during the growing season to relieve drought conditions or insect infestations.

The Department of Environmental Protection, working with the Cranberry Growers Association, developed an equation to estimate the amount of water needed in cranberry cultivation. The equation is based on a figure of 10 acre-feet of water per acre of cranberries under cultivation per year, or:

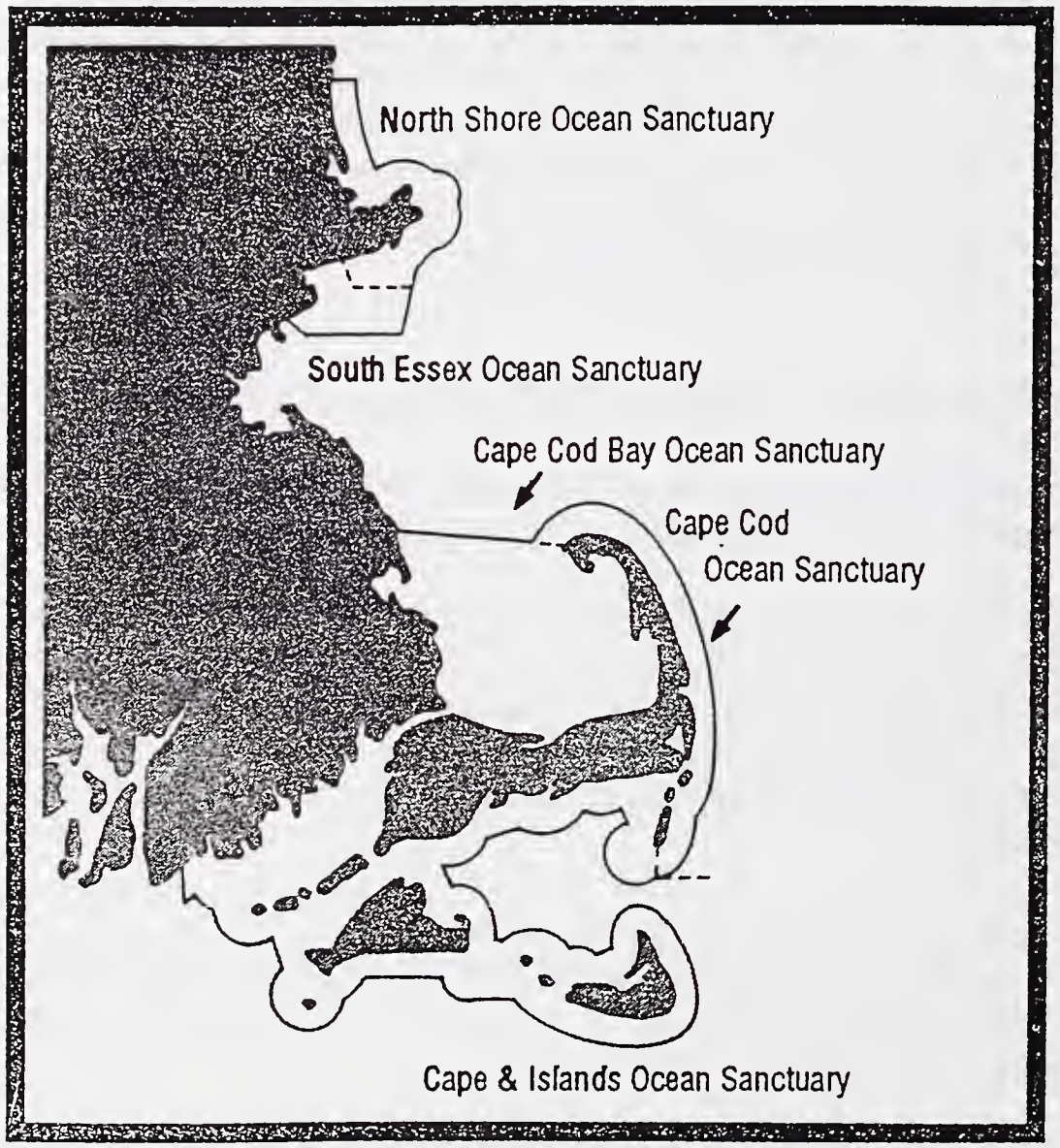
$$\text{mgd} = (\text{acres} \times 10 \text{ af} \times 0.325851) \div 365$$

Approximately 44 cranberry growers registered their water withdrawals with DEP under the WMA in 1988. Under WMA, registrants were required to register water use from 1980 to 1985. OWR has reviewed these registration forms. Individually, cranberry growers use an annual average of less than one mgd, but taken together as an industry, OWR has estimated that registered growers on Cape Cod use more than 9.40 mgd annually.

Figure 5

## Ocean Sanctuaries of Massachusetts

as defined by M.G.L.C. 132A ss. 13-16 and 18



# II. CAPE COD HYDROLOGY AND GROUND WATER MODELING

## A. Introduction

Cape Cod was formed during the Pleistocene Epoch by retreating glaciers which deposited sediments as they melted to the northwest. The glaciers formed moraines composed of till (sand, gravel, clay, and boulders) and outwash plains composed of sand and gravel. The thickness of the deposits range from about 100 feet at the Cape Cod Canal, to greater than 1,000 feet in the town of Truro. (LeBlanc et. al. 1986).

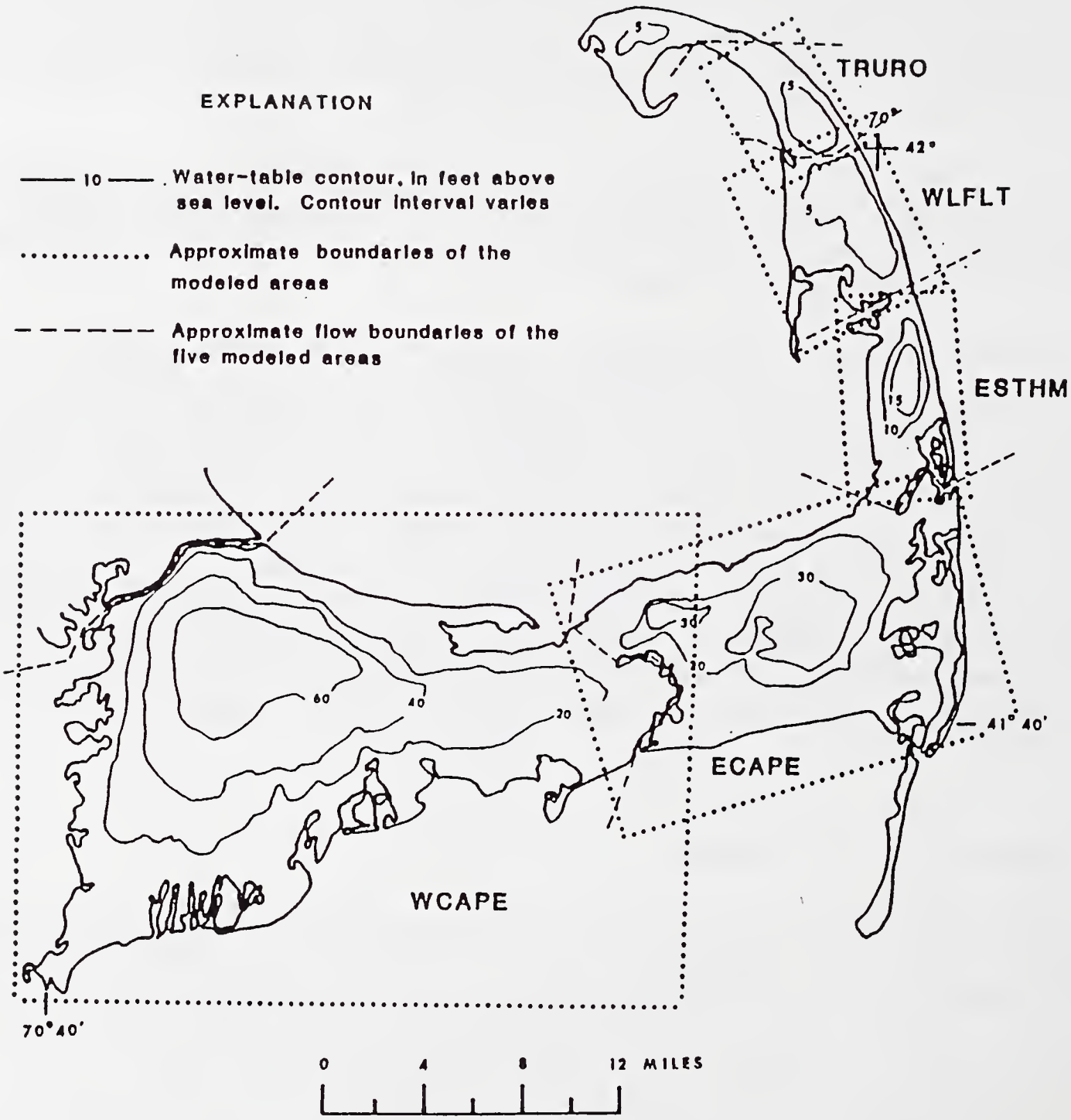
All natural recharge to the aquifer is in the form of precipitation. Cape Cod receives an annual average of 45 inches of rainfall, of which 45 to 48 percent actually recharges the aquifer system (LeBlanc et. al. 1986). The remaining rainfall is lost to evapotranspiration, springs, streams, marshes, and the ocean.

Approximately 96 percent of available water on Cape Cod is in ground water (the surface water is found mostly in the more than 350 kettlehole ponds left by the retreating glaciers). Ground water is the principal source of freshwater for domestic, industrial, and agricultural use on Cape Cod (Falmouth is the only community on Cape Cod which currently withdraws water from a surface water reservoir for public water supply). In addition to natural recharge from precipitation, water is recharged to the water table through wastewater discharge either through on-site septic systems or the three small municipal wastewater treatment plants in Falmouth, Hyannis and Chatham. Ground water discharge supports freshwater ponds and streams that in many areas are important habitats for plants and fish spawning and maturation. Streams and pond surfaces for the most part represent the intersection of the water table with land surface, although some ponds may be perched above the water table.

## B. Aquifer and flow cell description

Cape Cod consists of six ground water flow cells, or lenses, each of which is hydraulically independent under natural hydrologic conditions (LeBlanc and others 1986) and separated by tidal rivers (Figure 6). Because withdrawals in one flow cell will not impact an adjacent flow cell, each flow cell can be analyzed independently. These flow cells are bounded laterally, in part by surface water bodies, and by the salt water flow systems of Cape Cod Bay, Nantucket Sound, and the Atlantic Ocean. The interface between the fresh water and salt water flow systems forms the lateral and lower boundaries of the freshwater system, except where the freshwater cell is truncated by the underlying bedrock surface.

Figure 6


EXPLANATION
10 Water-table contour, in feet above sea level. Contour interval varies
Approximate boundaries of the modeled areas
Approximate flow boundaries of the five modeled areas
TRURO
WLFLT
ESTHM
ECAPE
WCAPE
70°
42°
41° 40'
70°40'
60
40
20
30
0 4 8 12 MILES

Cape Cod is completely surrounded and partially underlain by seawater. On the inner and mid-Cape, fresh water within the aquifer generally contacts bedrock. On the outer Cape, fresh water floats on seawater. Because fresh water is less dense than seawater, under normal conditions it will remain above the seawater, separated by a transition zone where some mixing will occur. Because the slope of Cape Cod is so gradual, there is little turbulence, and natural mixing of these layers is minor. Also, due to the difference in water chemistries of fresh and salt water, a boundary is formed that does not allow backflow of salt water landward into the fresh water. However, under conditions of low aquifer recharge and increased pumping from wells, the salt water will be pulled upward and inward and salt water may intrude into the fresh water wells. Thus far, this has only occurred in a few private wells in Truro.

Water in the flow cells forms mounds and flows downward toward the east and outward from the top of each ground water mound. A ground water divide traverses the Cape from west to east. This divide, similar to a surface water divide, is the highest elevation of the water table from which water will flow downward to either side. Water to the north of the divide generally flows northeast toward the Cape Cod Bay and the Atlantic Ocean. Water to the south of the divide generally flows southeast to the Nantucket Sound and Atlantic Ocean. Steady state flow through the aquifer, as established by the USGS, is estimated at 270 mgd.

USGS flow cell designations will be used throughout this report; however, the Cape Cod Planning and Economic Development Commission (CCPEDC 1987), now Cape Cod Commission, uses locally-developed names for the six lenses, as shown below in parentheses. Because the cells are hydrologically separate, sound water resource management techniques are contingent upon cell boundary rather than town boundary. The cells (and lenses) listed below include all or part of the following communities:

| West Cape (Sagamore) | East Cape (Monomoy) | Eastham (Nauset) | Wellfleet (Chequesset) | Truro (Pamet) | Provincetown (Pilgrim) |
|---|---|---|---|---|---|
| Barnstable | Orleans | Eastham | Wellfleet | Truro | Truro |
| Falmouth | Brewster | Wellfleet | Truro | 54% within | Provincetown |
| Mashpee | Chatham | 38% within | 70% within | National | 80% within National |
| Sandwich | Harwich | National | National | Seashore | Seashore |
| Bourne | Dennis | Seashore | Seashore | | |
| Yarmouth | Yarmouth | | | | |
| | Eastham | | | | |

Of the six flow cells on Cape Cod, only three, the West Cape, East Cape, and Truro cells, currently have sources of public water supply. The largest, West Cape, contributed an estimated 18.03 mgd (66 percent) to the Cape's water supply in 1989. Barnstable, Falmouth, Sandwich and Mashpee are totally dependent upon water supplies within the West Cape cell, while Bourne and Yarmouth received 1.24 mgd (7%) and 3.8 mgd (21%) of their public water supply from the West Cape cell.

Thirty-one percent of Cape Cod's total water supply is drawn from the East Cape flow cell. The East Cape cell supplied a total of 8.35 mgd to the communities of Dennis, Harwich, Brewster, Chatham, Orleans and Yarmouth. All six communities, with the exception of Yarmouth, are fully supplied by the East Cape. Yarmouth has recently developed three wells in the East Cape flow cell, and receives 10 percent, or 0.34 mgd, of its supply from this cell.

The Truro flow cell accounted for 0.92 mgd or 3 percent of the Cape's total water demand. This was used by the Town of Provincetown and a small portion of Truro, which derive 100% of its supply from this cell.

## C. Analysis of Ground Water Elevations and Flow

This analysis describes the ground water flow systems of Cape Cod and assesses the effects of changing patterns of ground water withdrawal and recharge to the surface and ground water hydrological systems on Cape Cod.

### 1. Description of the Hydrologic Models

In 1989, the U.S. Geological Survey in cooperation with the Department of Environmental Management's Office of Water Resources began an investigation to assess the effects of changing patterns of ground water withdrawal and recharge to the surface and ground water hydrological systems of the five independent, active flow cells of Cape Cod. This effort involved development of a model and execution of several sample runs by the USGS. The Office of Water Resources has updated projected pumping data of each municipal well on Cape Cod to simulate future stress conditions. Pumping rates are based on water needs forecasts approved by the Water Resources Commission and information from municipal water superintendents. All model assumptions (i.e. specified yield, horizontal hydraulic conductivity, well depths, etc.) and input data are the same as provided by the U.S. Geological Survey (Appendix C), except as provided in the following discussions. This includes changes in recharge to the aquifer system (to simulate a 1960's-type drought) as well as adjusting future pumping and well data to current projections. The main assumptions of the model are described below.

In-depth analysis of the hydrologic assumptions and techniques used in the model are described in the Draft USGS Water Supply Paper "Analysis of the Effects of Changing Pumpage and Recharge on Groundwater Flow in the Cape Cod, Martha's Vineyard and Nantucket Island Basins, Massachusetts" (Appendix C). These effects are reported as (1) changes in the water table altitudes for each flow cell; (2) changes in pond levels and streamflows for selected ponds and streams within the Cape Cod basin; and (3) changes in the position of the interface between freshwater and saltwater in the Truro flow Cell.

### 2. Assumptions of the Hydrologic Models

**Seasonal Ground Water Elevations** For the purpose of modeling, the water table configuration for the Cape Cod basin was characterized as six oblong mounds occupying the

six flow cells described above. The highest water table elevation corresponded to the highest land surface elevations. Ground water flows out radially from these high water table elevations toward streams between cells and the coastal discharge areas. Annual fluctuations at individual observation wells range from two to seven feet. Seasonal changes in aquifer recharge and ground water withdrawals also cause fluctuations in the water table elevations. The vast majority of lakes and streams of Cape Cod are hydraulically connected to the groundwater system, and therefore mirror the water table response to changing stress conditions. The highest annual water table elevations occur during early spring, when recharge is the greatest and groundwater withdrawals are low. The lowest water table elevations occur during the late summer when ground water recharge is minimal and water use is highest. Water table fluctuations vary in magnitude across the Cape, with the least amount of fluctuation generally near the shoreline.

The fresh ground water system is bounded laterally and at depth by the salt water system. Because fresh water is less dense than the surrounding salt water, lens-shaped bodies of freshwater, which are underlain by saltwater, are formed. The zone of mixing between the fresh and salt water systems is relatively thin; therefore, this transition zone is considered negligible and the fresh water-salt water interface is referred to as the "sharp" interface (Essaid 1990). Under normal hydrologic conditions, it is assumed that the fresh water and salt water systems are in hydrodynamic equilibrium. Ground water leaving the fresh water system as discharge to the shore is balanced by aquifer recharge from precipitation, resulting in a static interface between flow systems. Reductions in aquifer recharge and/or increases in groundwater withdrawals may result in a reduction in the rate of coastal discharge causing the landward movement of the saltwater/freshwater boundary.

**Water supplies** Five of the six flow cells have potential for future public water supply development, and these were analyzed for potential changes in ground water levels. Currently, the Eastham and Wellfleet flow cells do not have any public water supplies; however, because of the forecast water needs and the potential for water supply development in the Wellfleet flow cell, two hypothetical wells were modeled. Each flow cell was modeled using simulated average recharge (recharge to the aquifer which would occur during an average precipitation year) and drought recharge conditions (a 20 percent reduction in natural recharge over five years). In the historical record, these drought conditions approximate an event such as the mid-1960's drought. Both 1989 existing and proposed 2020 demand numbers were used to simulate well usage in the four flow cells excluding Eastham.

**Well Pumping** In the two largest flow cells, the East Cape and the West Cape, existing and future demands were broken down into a three month summer in-season demand and a nine month off-season demand to simulate actual pumping conditions. With input from the local water supply officials, in-season and off-season 2020 projected pumpage for each well was simulated. For the Wellfleet and Truro flow cells, pumping simulations consist of running (a) current average annual pumping (the average of in-season and off-season demand); (b) a very heavy pumping scenario of current in-season pumping for 12 months per year; and (c) a second heavy pumping scenario of 2020 in-season pumping for 12 months per year. For the West Cape, East Cape and Truro flow cells, the models simulate ground water withdrawals and recharge conditions during 1975 and 1989 and estimate conditions for 2020.

In addition, the simulations include seasonal fluctuations in ground water withdrawals and recharge during normal recharge conditions. For the Eastham and Wellfleet flow cells, the models simulate only predevelopment stress conditions as there are no large public water supply wells in these cells. Currently, the Cape Cod Commission is working with water suppliers in Eastham, Truro, Wellfleet, and Provincetown to address long-term water supply needs, and they will use this model and further refinements in their evaluations.

### 3. Ground Water Model Results

The results, displayed in the tables and maps in the following section, illustrate the impact of various pumping and recharge scenarios. See Appendix D for a complete list of modeled pumping well rates and flow cell node locations.

It is important to note that while the model provides a valuable indication of the relative importance of precipitation and pumping for the Cape's ground and surface waters, the specific conclusions from the model runs are not predictive of the response to pumping of all water bodies. Specific ponds and other water bodies included in the model and the impacts of the scenarios are shown in the following sections of the report. In some cases, pumping wells can have significant impacts on water levels of a nearby water body or water course and may affect the area's biota; however, this study does not include an assessment of impacts on fisheries, habitats, or other biological resources.

A key finding is that, at the flow cell level, both seasonal as well as climatic (drought) conditions have greater impacts on the modeled water bodies on Cape Cod than do current or future water supply withdrawals. The largest change in modeled pond elevation is due to a reduction in precipitation and recharge. A five-year, 20 percent reduction in precipitation and ground water recharge was used to simulate a significant drought event. Drought recharge conditions and current demands were compared with normal recharge conditions and higher 2020 demands to assess the potential impacts on ground water levels.

In the West Cape Lens, the current water withdrawn by public water supply agencies averages 25.76 mgd in-season, and 12.86 mgd off-season.

- Under current demands and drought recharge conditions, the average water table level for the flow cell was 3.93 feet lower than under normal recharge conditions.

- Water needs in 2020 are expected to increase nearly 45 percent in-season and nearly 51 percent off-season. Running the model with these higher 2020 demands under normal recharge conditions, there is no measureable change in water table levels (at USGS observation wells) attributable to this increase in pumping.

In the East Cape Lens, the current water withdrawn by public water supply agencies averages 11.65 mgd during June, July and August (in-season) and 5.19 mgd September through May (off-season).

- Under current demands and drought recharge conditions, the average water table level for the flow cell was 3.4 feet lower than under normal recharge conditions.

- Water needs in 2020 are expected to increase by nearly 35 percent in-season and nearly 49 percent off-season. Running the model with these higher 2020 demands under normal recharge conditions, the average decline in water table levels (at USGS observation wells) attributable to this increased pumping averages 0.3 feet, or about one-tenth the change under drought conditions.

In terms of impact on the aquifer volumes or water availability, the modeled changes are not considered significant from a regional perspective. The model grid size used is ¼ mile (1,320 ft.$^2$), and results depend on the amount and accuracy of input data for each grid area. With additional modeling using more hydrogeologic data and a finer grid, it is possible to address more localized issues related to changes in ground water levels.

The figures, particularly Water Surface Elevations for Selected Flow Cell Ponds (Figures 18, 19 and 30), clearly indicate the impacts of man-made and natural changes to the water tables of the flow cells. On Cape Cod, most ponds are formed in kettle holes whose elevation is a continuation of the surrounding water table. Several pond systems have been graphed within each flow cell, reflecting a range of elevations, geologic conditions, and adjacent pumping influences.

In the West Cape and East Cape flow cells, the public water supply pumping scenarios include the modest impact of off-season pumping under normal precipitation and recharge conditions (Figures 14 and 26). This has been compared with the current in-season (summer) pumping demand under normal and drought recharge conditions (Figures 16 and 28) as well as future projected pumping in 2020 under normal precipitation and normal recharge to the water table (Figures 17 and 29). Pond levels respond slightly when wells pump to meet the increased summer demand (Figures 18, 19, 30). Also during the summer, recharge to the water table through rainfall and infiltration is essentially non-existent, the main source being wastewater return flows (i.e., septic systems).

**D. Graphic and tabular results of model scenarios**

Results for each of the modeled ground water flow cells are presented in the following tables and figures, which include:

- A summary of public water supply pumping by each water supplier and each well under various scenarios
- Individual Town maps which locate each water supply well in the cell
- A map of lakes, ponds, and rivers modeled in each cell
- Maps showing changes in ground water elevation under various scenarios
- Tables summarizing the changes in pond levels and stream flows
- Graphics showing changes in pond water surface elevation under various scenarios

The results are shown in the following order: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| 3 | Wellfleet Flow Cell | 74 |
| 4 | Eastham Flow Cell | 75 |
| 5 | Provincetown Flow Cell | 75 |
| 6 | Truro Flow Cell | 83 |

1. West Cape Flow Cell


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| Figure 9 | Falmouth Public water supply wells | 45 |
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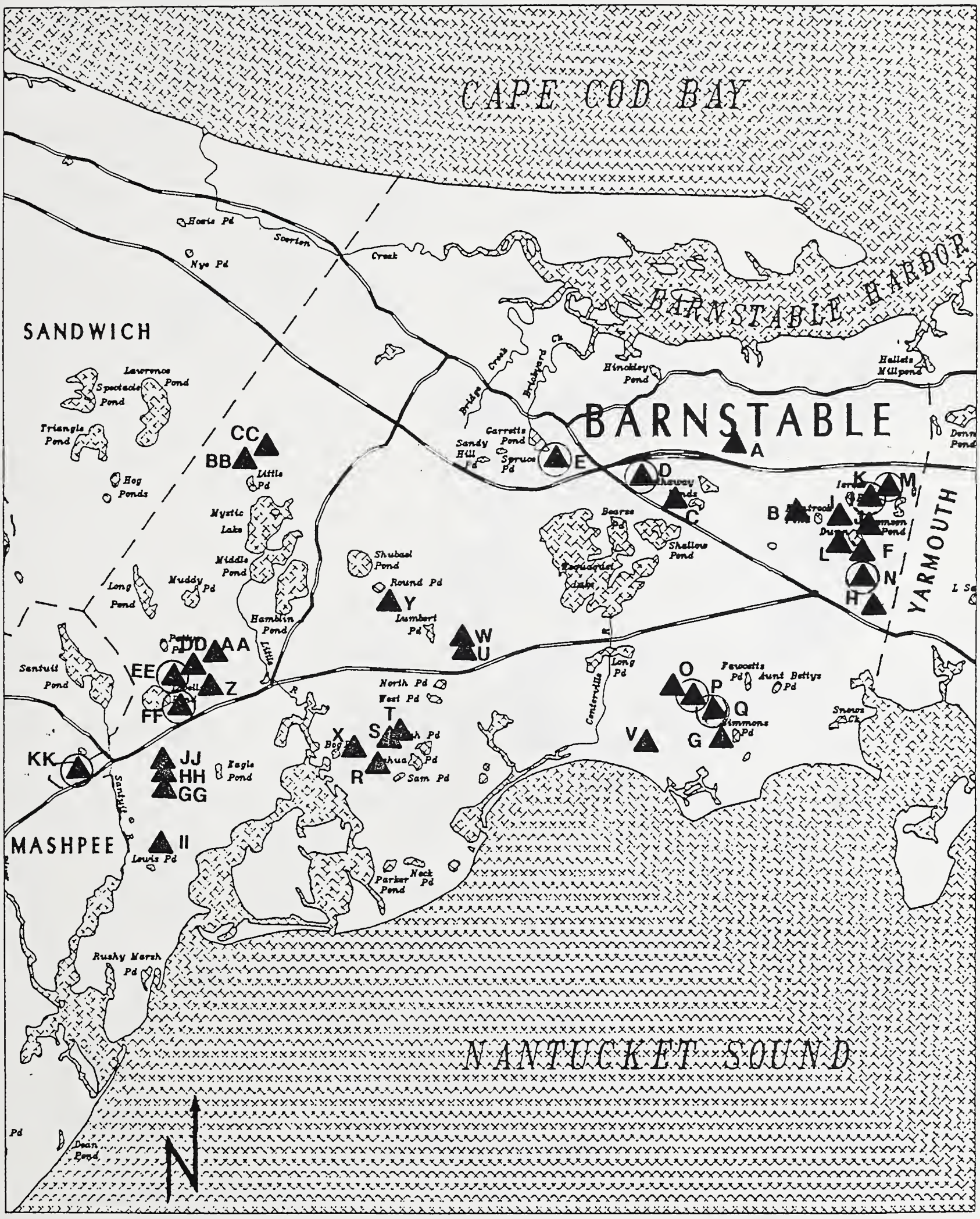
**The West Cape Flow Cell** (The Sagamore Lens), the largest of the five potable flow cells of Cape Cod, is approximately 16 miles from north to south and approximately 24 miles from east to west. The cell encompasses the towns of Bourne, Sandwich, Falmouth, Mashpee, Barnstable, and most of Yarmouth. The northern border is Cape Cod Bay and Cape Cod Canal to the northwest. The cell's eastern edge extends to Bass River and Chase Garden Creek in Yarmouth. The southern border is Vineyard Sound and Nantucket Sound. Its western border is Buzzards Bay. The water table elevation ranges from nearly sea level at the discharge boundaries located along the Cape Cod shoreline to nearly 70 feet above sea level in central Sandwich. The West Cape flow cell contains several streams and many kettle-hole ponds.

**Table 14**
**West Cape Flow Cell Pumping Summary**
million gallons per day

| Community | Map Symbol | 1989 In-Season Pumpage | 1989 Off-Season Pumpage | Projected 2020 In-Season Pumpage | Projected 2020 Off-Season Pumpage | Pumping Capacity |
|---|---|---|---|---|---|---|
| Barnstable FD | A-E | 0.74 | 0.33 | 1.00 | 0.51 | 3.24 |
| Barnstable WC | F-Q | 4.32 | 2.48 | 4.65 | 2.89 | 13.25 |
| C-O-MM | R-FF | 4.40 | 1.68 | 5.69 | 2.56 | 15.61 |
| Cotuit FD | GG-KK | 0.70 | 0.29 | 0.76 | 0.33 | 4.47 |
| Bourne WD | A-G | 1.59 | 0.77 | 1.97 | 1.21 | 6.03 |
| S. Sagamore WD | H | 0.20 | 0.08 | 0.18 | 0.10 | 0.33 |
| Otis Air N.G. | AA-BB | 0.58 | 0.41 | 0.58 | 0.39 | 2.94 |
| Falmouth | A-H | 5.36 | 2.87 | 6.56 | 3.64 | 16.40 |
| Mashpee WD | A-G | 0.31 | 0.21 | 2.50 | 0.61 | 6.25 |
| Sandwich WD | A-G | 1.76 | 0.99 | 2.87 | 1.95 | 8.81 |
| Yarmouth | A-S;W,X | 5.55 | 2.58 | 9.41 | 4.70 | 15.95 |
| TOTAL | | 25.51 | 12.69 | 36.17 | 18.89 | 93.28 |

DEM Office of Water Resources

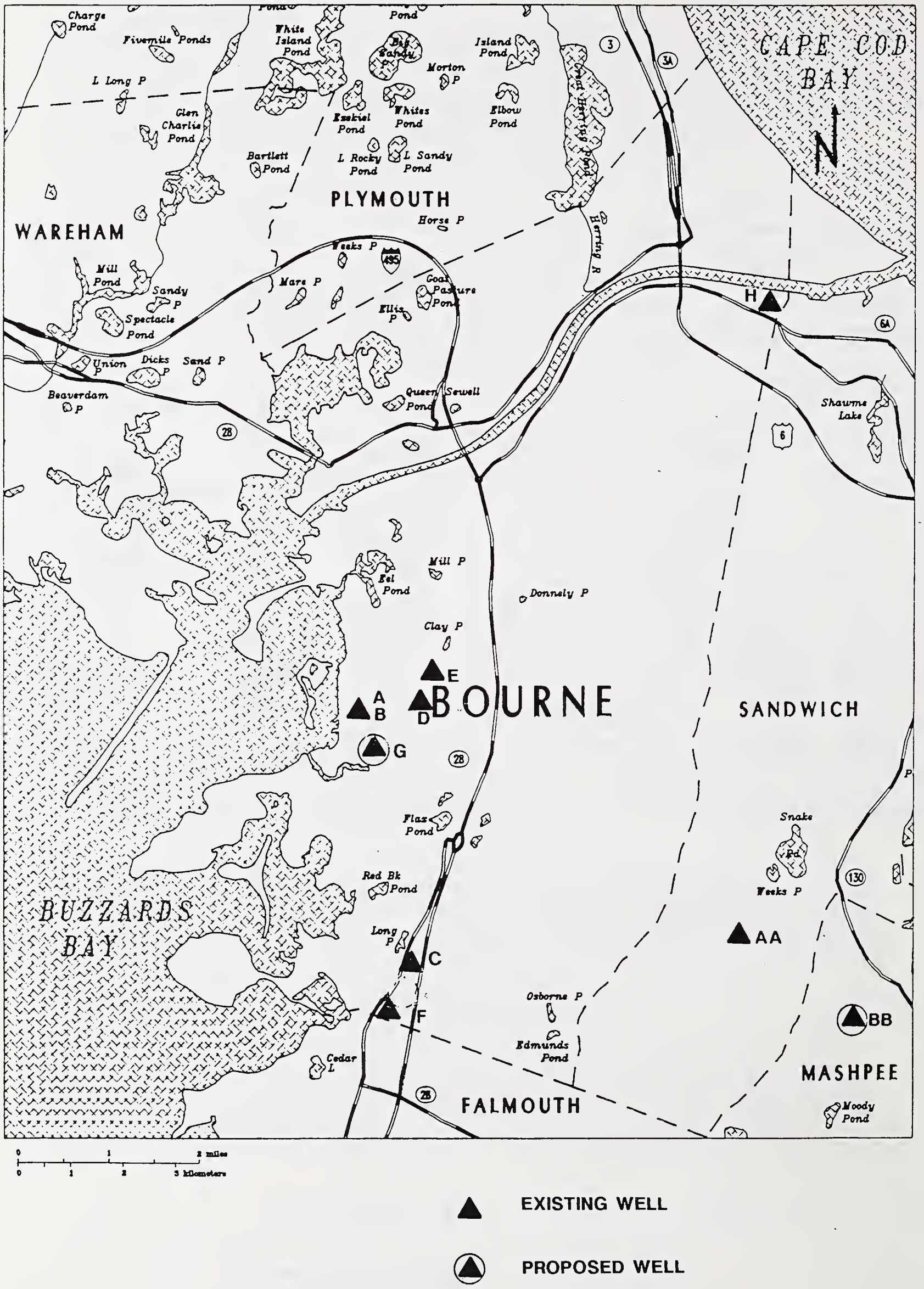
Note: See Appendix D for pumping data for individual wells. Pumping capacities are a summation of each existing and proposed water supply source. Pumping capacity data was provided by DEP for existing sources. Capacity for proposed sources was provided by communities.




0 1 2 miles
0 1 2 3 kilometers

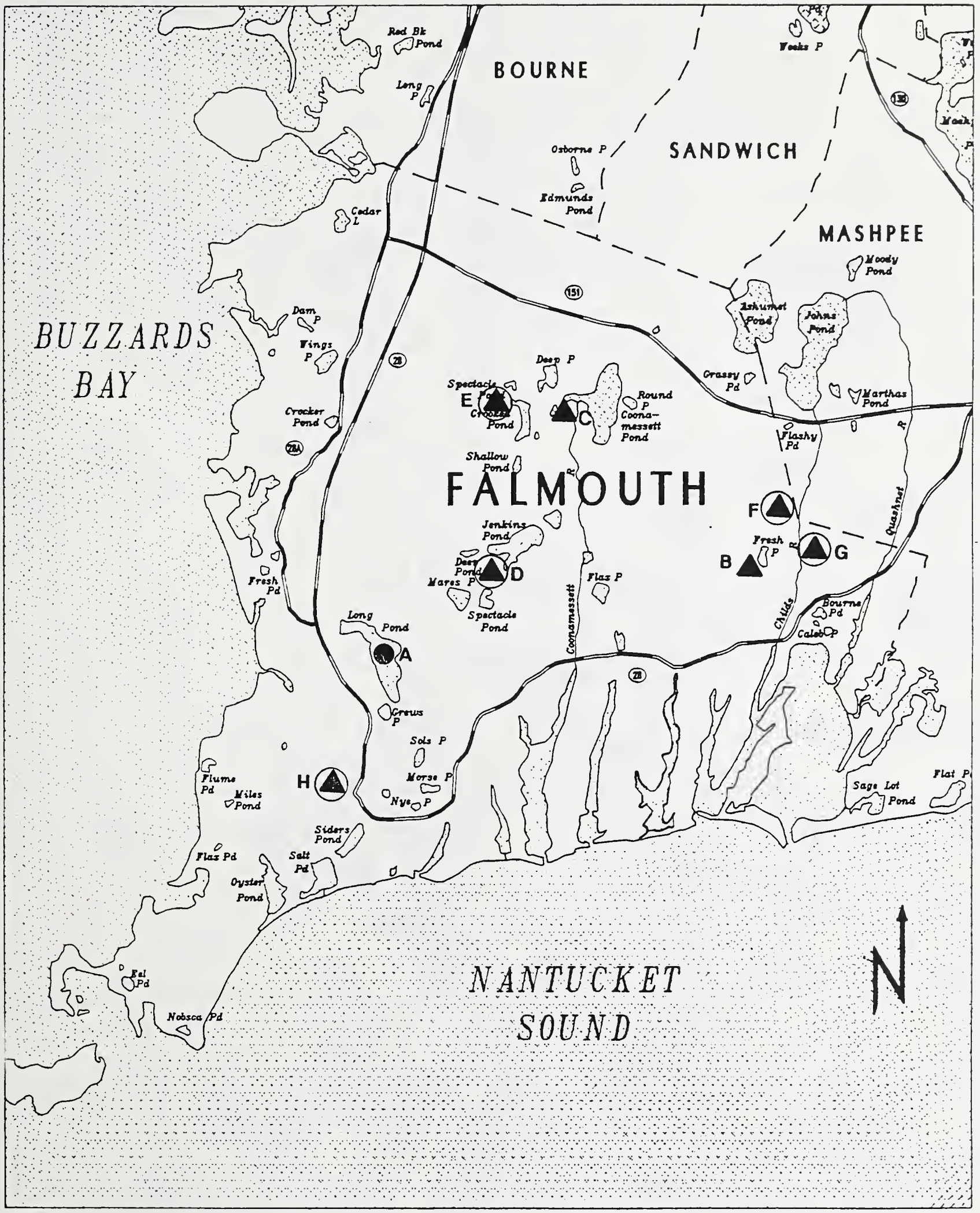
▲ EXISTING WELL

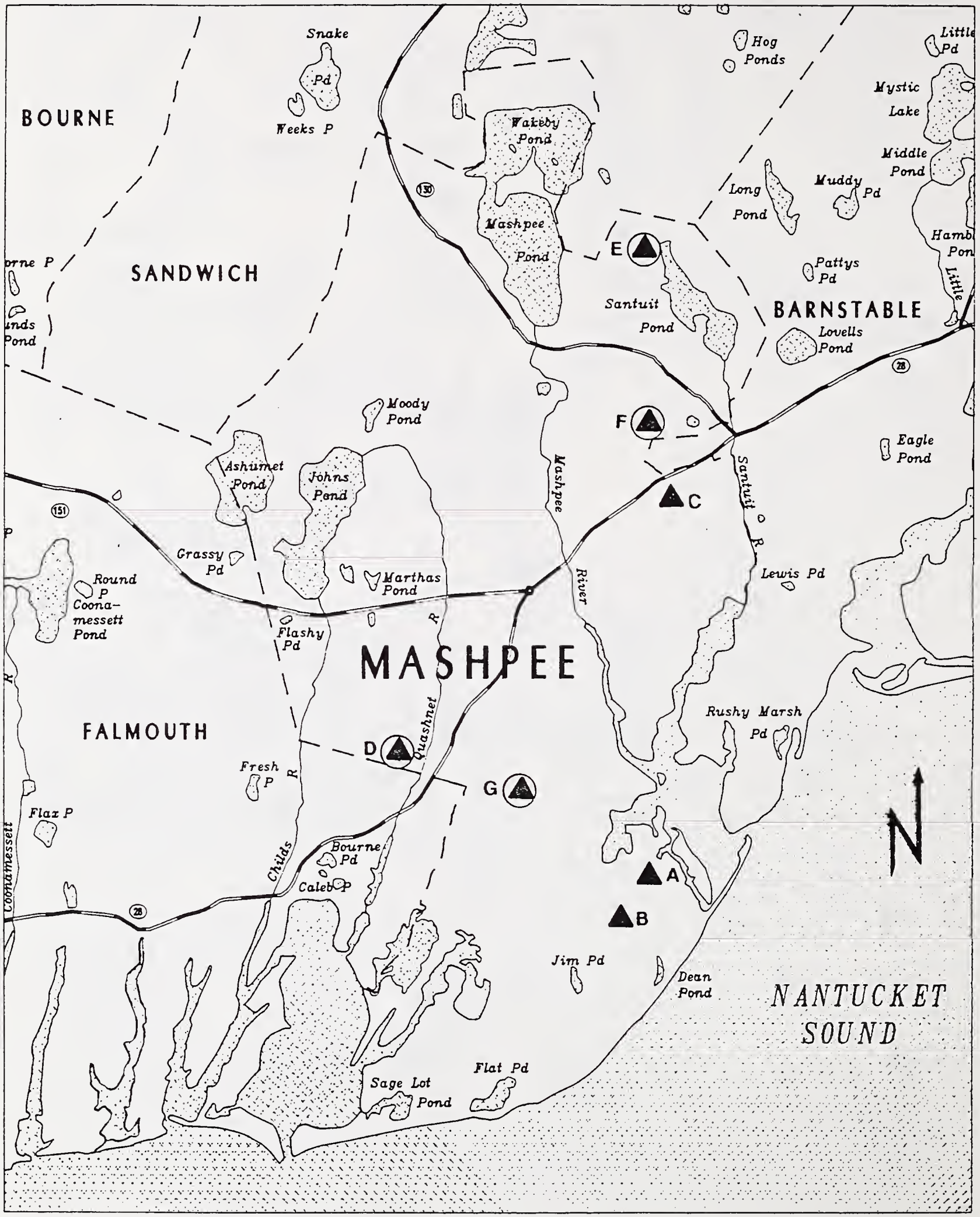
PROPOSED WELL




EXISTING WELL

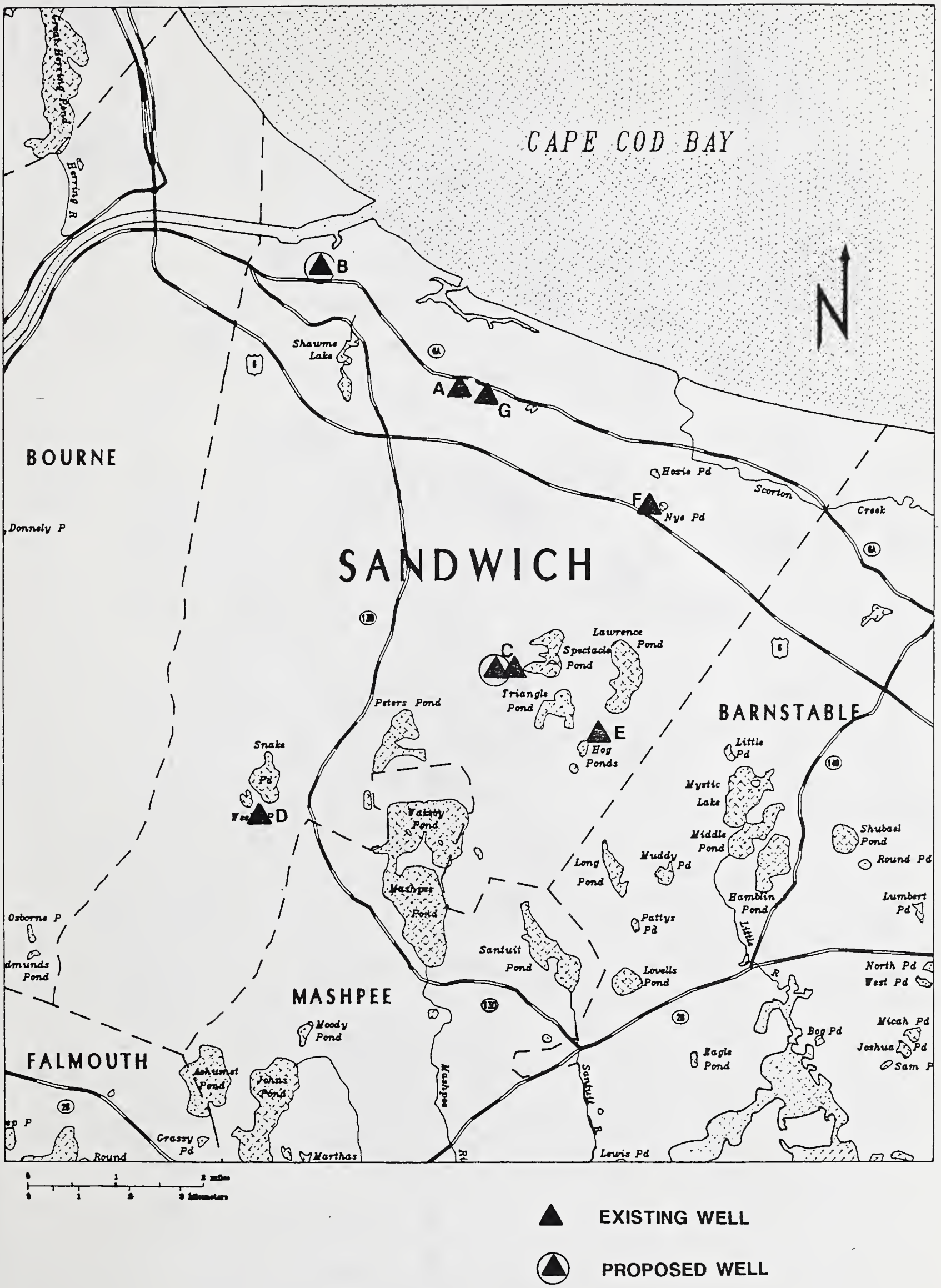
PROPOSED WELL


BOURNE
SANDWICH
MASHPEE
FALMOUTH
BUZZARDS BAY
NANTUCKET SOUND
N
Red Bk Pond
Long P
Weeks P
Osborne P
Edmunds Pond
Cedar L
Moody Pond
Ashumet Pond
Johns Pond
Dam P
Wings P
Deep P
Spectacle Pond
Round P
Coonamessett Pond
Grassy Pd
Marthas Pond
Crocker Pond
Flashy Pd
Shallow Pond
Jenkins Pond
Deep Pond
Mares P
Spectacle Pond
Fresh P
Flax P
Bourne Pd
Caleb P
Long Pond
Coonamessett
Quashnet
Childs
Fresh Pd
Grews P
Sols P
Morse P
Nye P
Flume Pd
Miles Pond
Siders Pond
Flax Pd
Salt Pd
Oyster Pond
Sage Lot Pond
Flat P
Fal Pd
Nobsca Pd
A
B
C
D
E
F
G
H
0 1 2 miles
0 1 2 3 kilometers
RESERVOIR
EXISTING WELL
PROPOSED WELL




EXISTING WELL

PROPOSED WELL


CAPE COD BAY
N
Great Herring Pond
Herring R
B
Shawme Lake
A
G
BOURNE
Hoxie Pd
Scorton
Creek
F
Nye Pd
Donnely P
SANDWICH
Lawrence Pond
Spectacle Pond
C
Triangle Pond
Peters Pond
BARNSTABLE
E
Hog Ponds
Little Pd
Snake Pd
D
Mystic Lake
Middle Pond
Shubael Pond
Round Pd
Long Pond
Muddy Pd
Hamblin Pond
Lumbert Pd
Osborne P
Pattys Pd
Santuit Pond
Lovells Pond
North Pd
West Pd
MASHPEE
Moody Pond
Micah Pd
Bog Pd
Joshua Pd
Sam P
FALMOUTH
Eagle Pond
Ashumet Pond
Johns Pond
Mashpee
Santuit R
Grassy Pd
Marthas
Lewis Pd
Round
EXISTING WELL
PROPOSED WELL

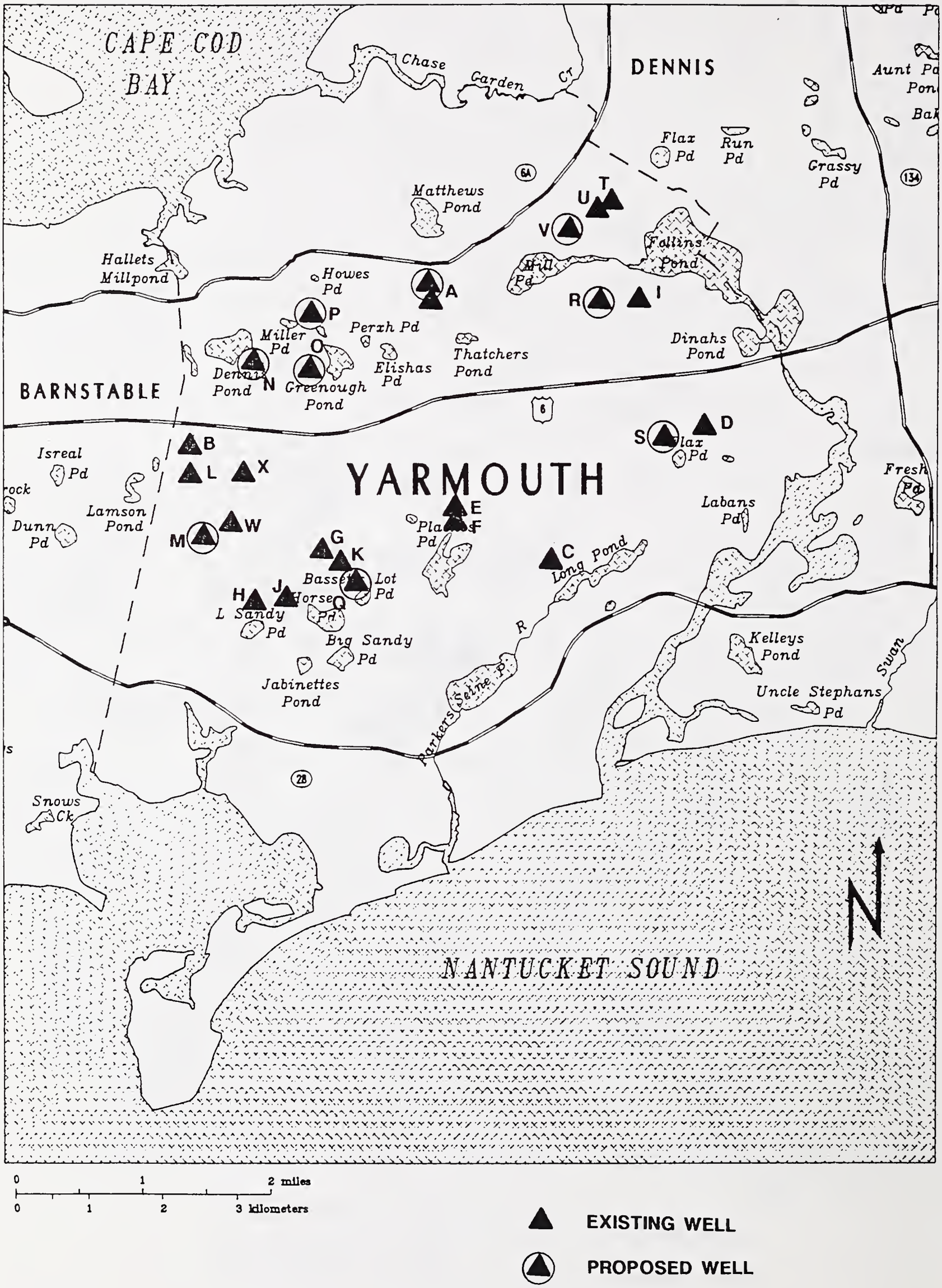
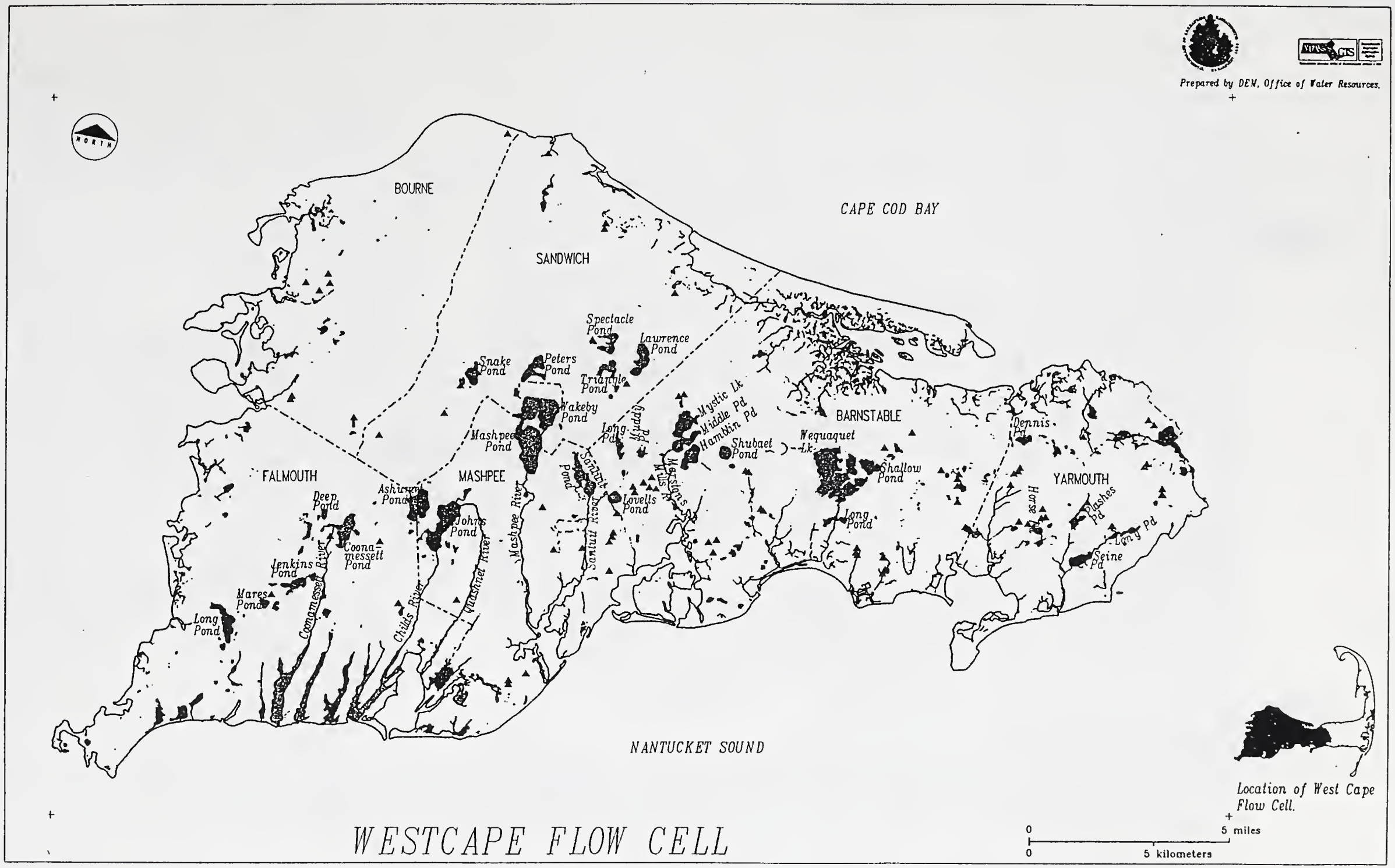

CAPE COD BAY
Chase Garden Cr
DENNIS
Aunt Pd Pond
Bak
Flax Pd
Run Pd
Grassy Pd
6A
134
Matthews Pond
T
U
V
Hallets Millpond
Howes Pd
A
Mill Pd
Collins Pond
R
I
P
Perch Pd
Miller Pd
O
Dennis Pond
N
Greenough Pond
Elishas Pd
Thatchers Pond
Dinahs Pond
BARNSTABLE
6
S
D
Flax Pd
B
Isreal Pd
L
X
YARMOUTH
Fresh Pd
Lamson Pond
Dunn Pd
M
W
E
F
Plains Pd
Labans Pd
G
K
C
Long Pond
Bassett
Lot Pd
H
J
Horse Pd
Q
L Sandy Pd
Big Sandy Pd
Kelleys Pond
Swan
Jabinettes Pond
Seine P
Parkers R
Uncle Stephans Pd
28
Snows Ck
N
NANTUCKET SOUND
0 1 2 miles
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

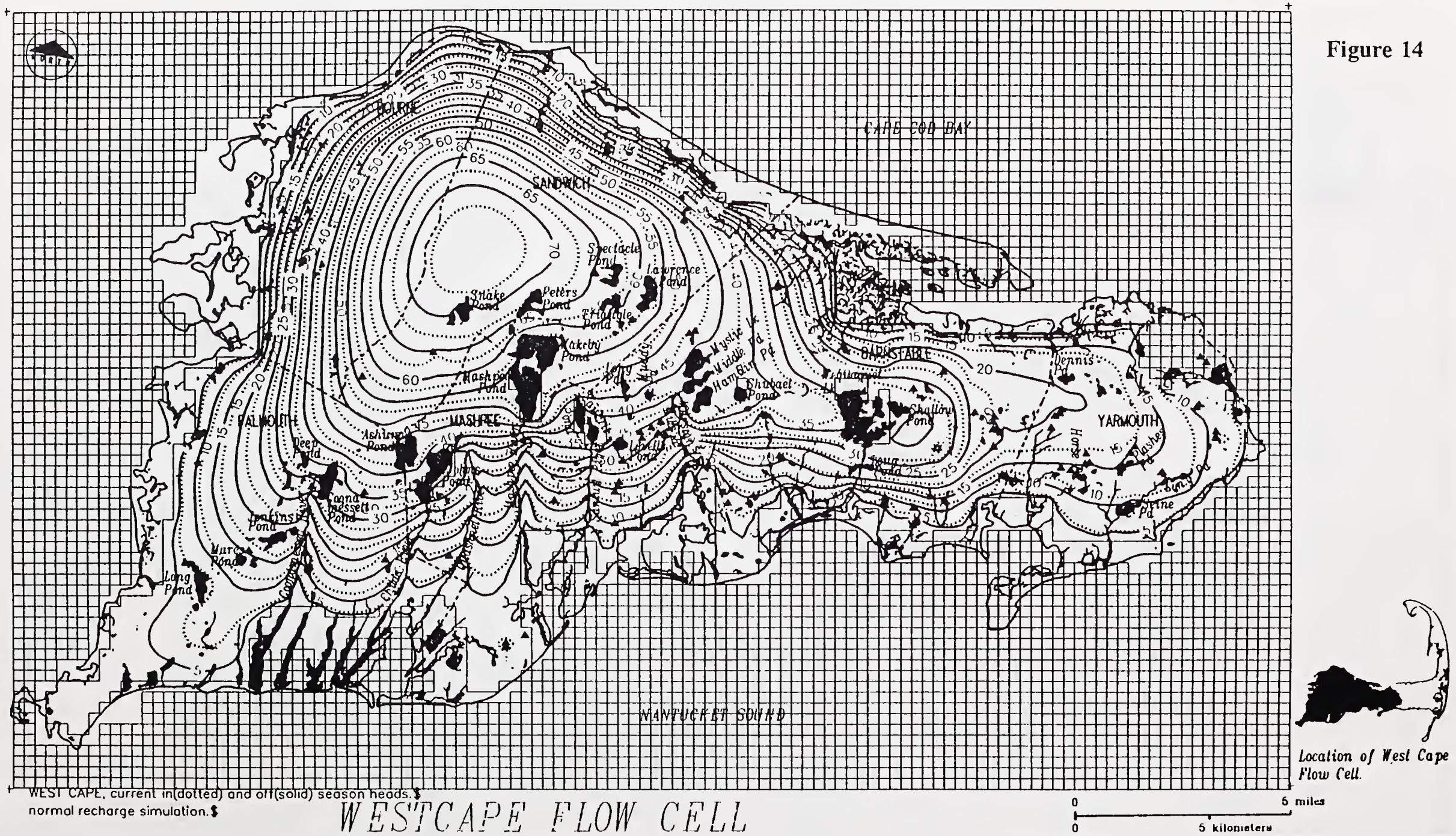
Figure 13




LAKES,PONDS AND RIVERS MODELED IN WEST CAPE FLOW CELL

Prepared by DEM, Office of Water Resources

Figure 14



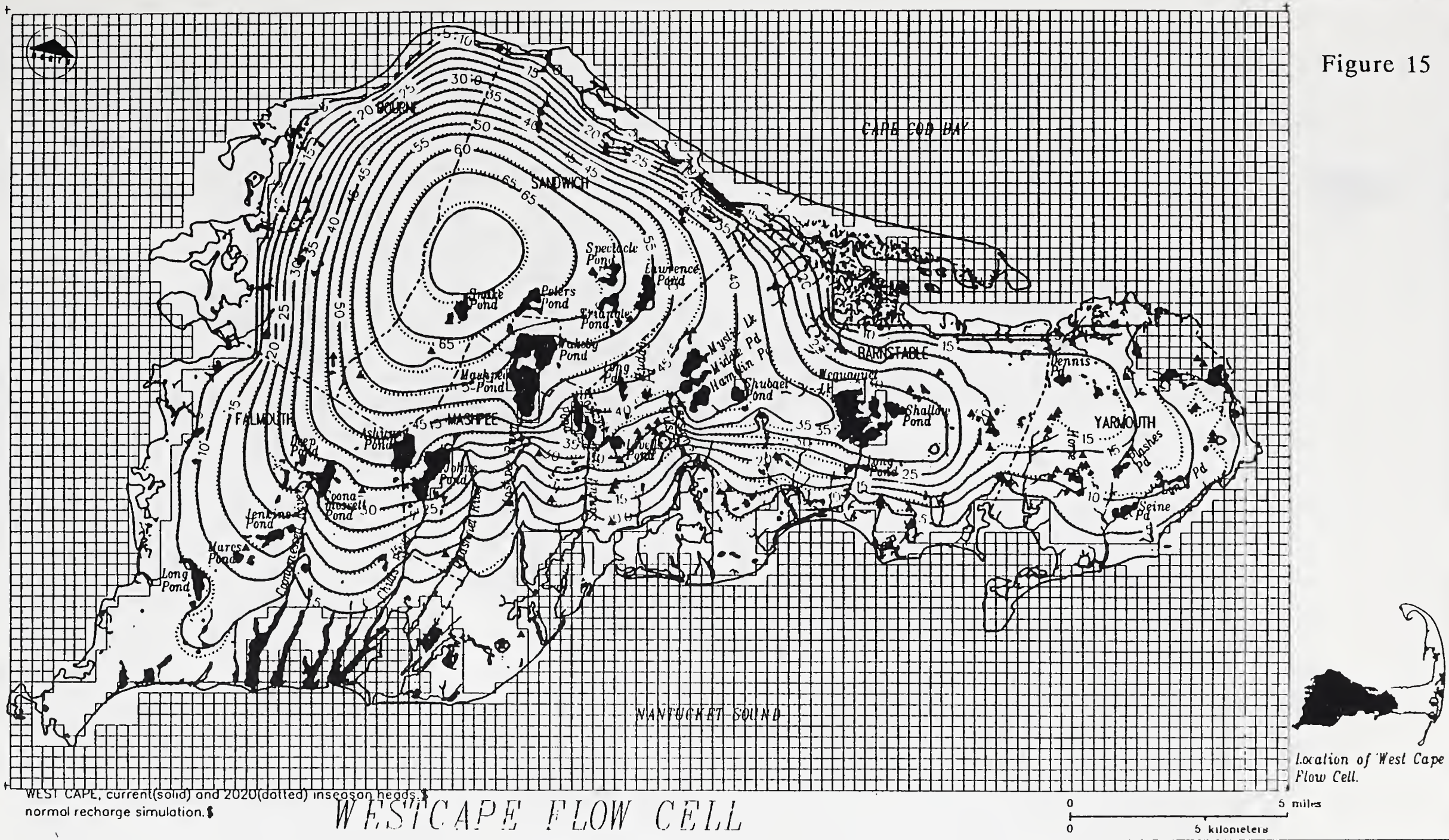

WEST CAPE, current in(dotted) and off(solid) season heads.$
normal recharge simulation.$

WESTCAPE FLOW CELL

**Heads Resulting From Current Off-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (dotted line)**

Prepared by DEM. Office of Water Resources.

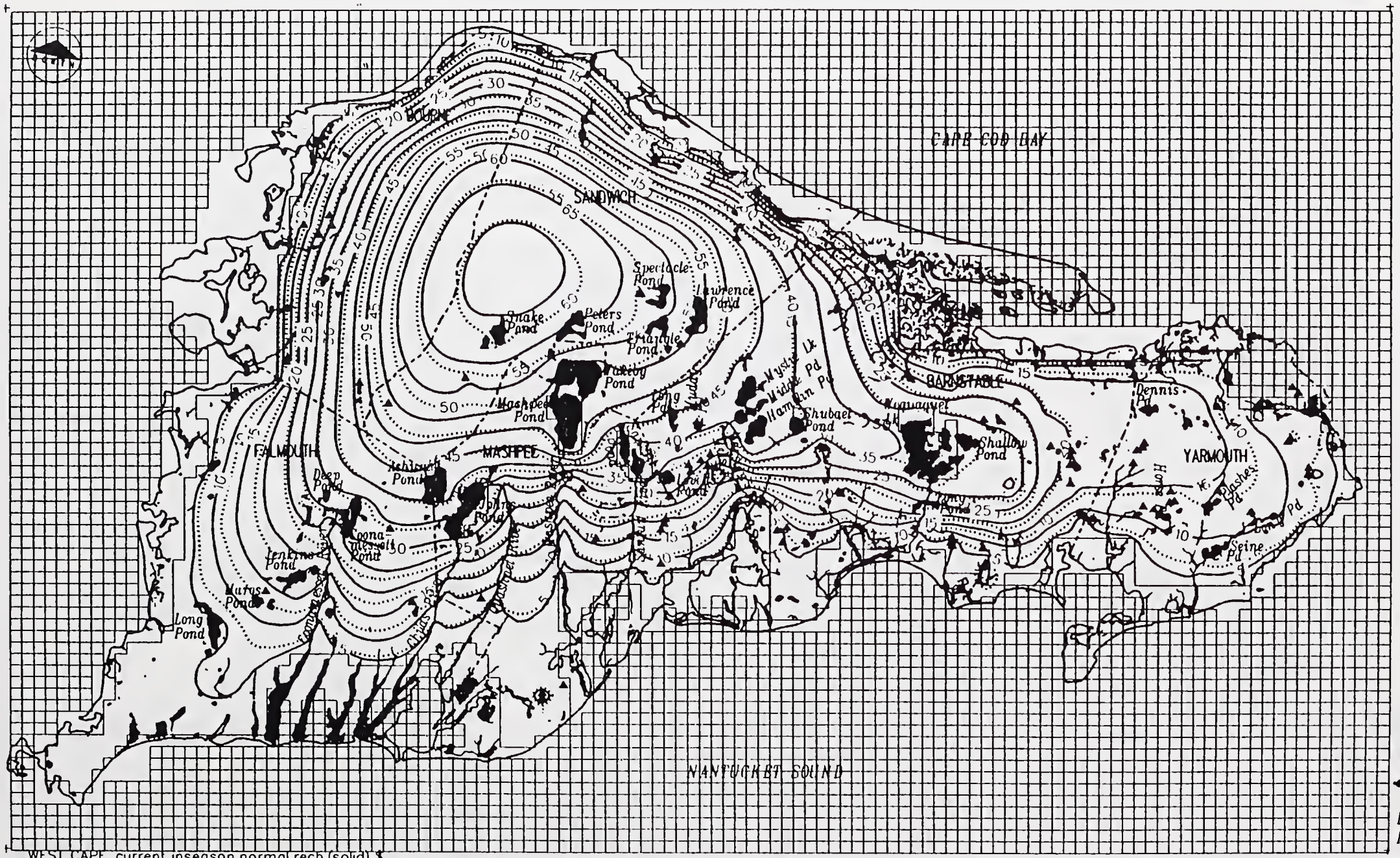
Figure 15




**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Proposed 2020 In-Season Pumping Under Normal Recharge Conditions (dotted line)**

Prepared by DEM, Office of Water Resources.

Figure 16



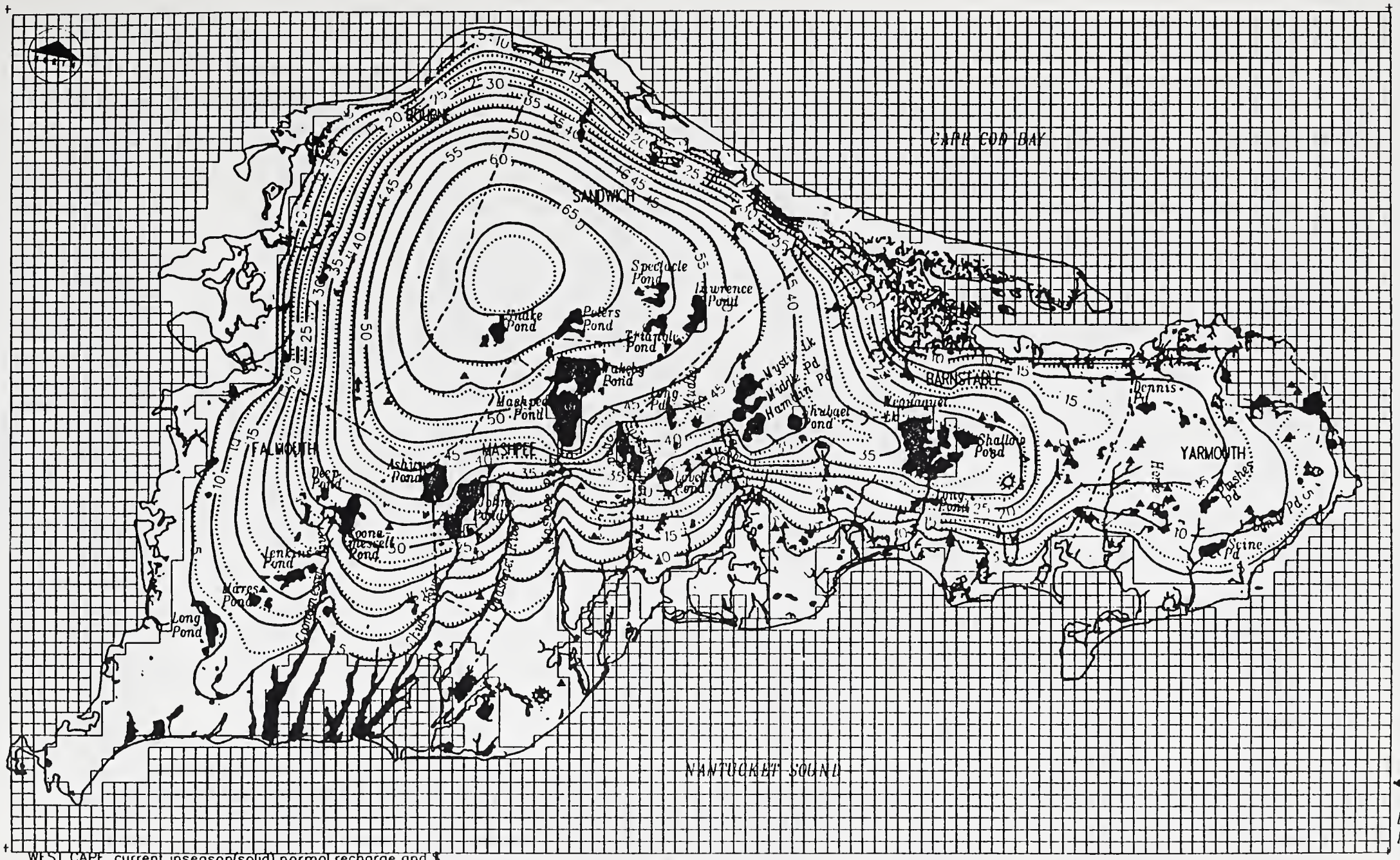

WEST CAPE, current inseason normal rech.(solid),$
and current inseason drought(dotted) heads.$

Location of West Cape Flow Cell.

**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Current In-Season Pumping Under Drought Recharge Conditions (dotted line)**

Prepared by DEM, Office of Water Resources

Figure 17




**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Proposed 2020 In-Season Pumping Under Drought Conditions (dotted line)**

# Table 15

Calculated Pond Levels[1] for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in feet above NGVD*
West Cape Flow Cell

| Pond Name | Pond Levels During Existing Inseason Pumpage Under Average Recharge Conditions | Pond Levels During 2020 Inseason Pumpage Under Average Recharge Conditions | Pond Levels During Existing Offseason Pumpage Under Average Recharge Conditions | Pond Levels During 2020 Offseason Pumpage Under Average Recharge Conditions | Pond Levels During Existing Inseason Pumpage Under Drought Recharge Conditions | Pond Levels During 2020 Inseason Pumpage Under Drought Recharge Conditions | Pond Levels During Existing Offseason Pumpage Under Drought Recharge Conditions | Pond Levels During 2020 Offseason Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| BARNSTABLE | | | | | | | | |
| Long Pond | 44.43 | 43.50 | 45.39 | 44.56 | 39.85 | 40.35 | 45.39 | 41.33 |
| Lovells Pond | 30.29 | 29.68 | 31.85 | 31.38 | 27.30 | 27.62 | 31.85 | 29.11 |
| Muddy Pond | 41.05 | 39.98 | 42.15 | 41.27 | 36.84 | 37.11 | 42.15 | 38.31 |
| Mystic Lake | 43.18 | 42.73 | 44.08 | 43.63 | 38.27 | 39.37 | 44.08 | 40.23 |
| Middle Pond | 43.17 | 42.73 | 44.03 | 43.59 | 38.27 | 39.38 | 44.03 | 40.21 |
| Hamblin Pond | 43.15 | 42.72 | 44.01 | 43.57 | 38.27 | 39.37 | 44.01 | 40.19 |
| Shubael Pond | 41.00 | 41.60 | 42.02 | 42.58 | 35.51 | 37.83 | 42.02 | 38.71 |
| Waquaquet Pond | 34.20 | 34.52 | 34.65 | 34.95 | 30.32 | 31.73 | 34.65 | 32.17 |
| Long Pond | 23.24 | 23.72 | 23.83 | 24.27 | 20.04 | 21.40 | 23.83 | 21.90 |
| Shallow Pond | 34.20 | 34.51 | 34.69 | 34.98 | 30.29 | 31.68 | 34.69 | 32.16 |
| FALMOUTH | | | | | | | | |
| Long Pond | 4.91 | 4.31 | 6.42 | 5.96 | 2.74 | 2.79 | 6.42 | 4.29 |
| Mares Pond | 12.65 | 12.46 | 14.12 | 13.81 | 10.00 | 10.62 | 14.12 | 11.69 |
| Jenkins Pond | 16.81 | 16.75 | 17.83 | 17.66 | 14.18 | 14.93 | 17.83 | 15.64 |
| Deep Pond | 33.19 | 33.67 | 34.61 | 34.80 | 28.91 | 30.76 | 34.61 | 31.67 |
| Coonamesset Pond | 32.27 | 32.65 | 33.24 | 33.49 | 28.95 | 30.44 | 33.24 | 31.18 |
| MASHPEE | | | | | | | | |
| Ashumet Pond | 41.40 | 41.81 | 42.41 | 42.80 | 36.86 | 38.76 | 42.41 | 39.61 |
| Johns Pond | 34.55 | 34.87 | 35.30 | 35.55 | 31.45 | 32.87 | 35.30 | 33.49 |
| Wakeby Pond | 53.19 | 53.34 | 53.83 | 53.92 | 48.72 | 50.26 | 53.83 | 50.83 |
| Mashpee Pond | 52.56 | 52.72 | 53.20 | 53.30 | 48.15 | 49.68 | 53.20 | 50.25 |
| Santuit Pond | 38.22 | 37.83 | 38.92 | 38.55 | 34.97 | 35.55 | 38.92 | 36.18 |
| SANDWICH | | | | | | | | |
| Snake Pond | 68.48 | 69.19 | 69.71 | 70.30 | 60.12 | 63.51 | 69.71 | 64.58 |
| Peters Pond | 64.62 | 64.76 | 65.56 | 65.69 | 57.75 | 60.07 | 65.56 | 60.98 |
| Spectacle Pond | 60.65 | 59.58 | 61.75 | 60.77 | 53.40 | 54.63 | 61.75 | 55.80 |
| Triangle Pond | 58.87 | 57.55 | 59.95 | 58.66 | 52.11 | 52.77 | 59.95 | 53.91 |
| Lawrence Pond | 55.05 | 54.13 | 55.25 | 55.15 | 48.47 | 49.65 | 56.04 | 50.64 |
| YARMOUTH | | | | | | | | |
| Dennis Pond | 18.12 | 17.88 | 19.39 | 19.13 | 13.72 | 14.62 | 19.64 | 15.58 |
| Horse Pond | 11.10 | 9.82 | 12.16 | 10.85 | 7.98 | 7.41 | 12.56 | 8.20 |
| Plashes Pond | 13.23 | 12.12 | 14.26 | 13.27 | 9.90 | 9.55 | 14.59 | 10.45 |
| Seine Pond | 8.29 | 7.86 | 8.68 | 8.29 | 6.14 | 6.18 | 8.87 | 6.47 |
| Long Pond | 10.31 | 9.46 | 10.92 | 10.26 | 7.84 | 7.51 | 11.15 | 8.13 |

*National Geodetic Vertical Datum

1. Calculated Pond levels are relative rather than absolute. Actual pond levels may vary.

# Table 16

Calculated Streamflows[1] for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in cubic feet per second
West Cape Flow Cell

| River System | Streamflow During Existing Inseason Pumpage Under Average Recharge Conditions | Streamflow During 2020 Inseason Pumpage Under Average Recharge Conditions | Streamflow During Existing Offseason Pumpage Under Average Recharge Conditions | Streamflow During 2020 Offseason Pumpage Under Average Recharge Conditions | Streamflow During Existing Inseason Pumpage Under Drought Recharge Conditions | Streamflow During 2020 Inseason Pumpage Under Drought Recharge Conditions | Streamflow During Existing Offseason Pumpage Under Drought Recharge Conditions | Streamflow During 2020 Offseason Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| Coonamesett River | 6.58 | 6.96 | 10.62 | 10.77 | 3.75 | 5.03 | 6.39 | 7.77 |
| Childs River | 3.03 | 3.14 | 5.97 | 6.08 | 1.81 | 2.25 | 3.69 | 4.54 |
| Quashnet River | 10.69 | 10.90 | 16.17 | 16.32 | 8.04 | 8.14 | 11.69 | 13.13 |
| Mashpee River | 8.91 | 8.88 | 12.39 | 12.34 | 6.14 | 7.01 | 8.36 | 9.54 |
| Santuit River | 2.48 | 2.29 | 4.46 | 4.23 | 1.33 | 1.49 | 2.63 | 2.99 |
| Marstons Mills R. | 1.97 | 1.80 | 3.70 | 3.65 | 0.80 | 0.95 | 1.52 | 2.04 |
| Centerville River | 1.24 | 1.34 | 1.40 | 1.47 | 0.89 | 1.08 | 1.02 | 1.18 |

[1] Calculated streamflows are relative rather than absolute. Actual streamflows may be greater or less than indicated values. Due to an artifact of the model associated with wastewater flows, streamflows under 2020 pumpage conditions may not in reality be greater than those under existing conditions as indicated. However the model does indicate that streamflows do not significantly change due to increases in pumping in 2020.

Figure 18

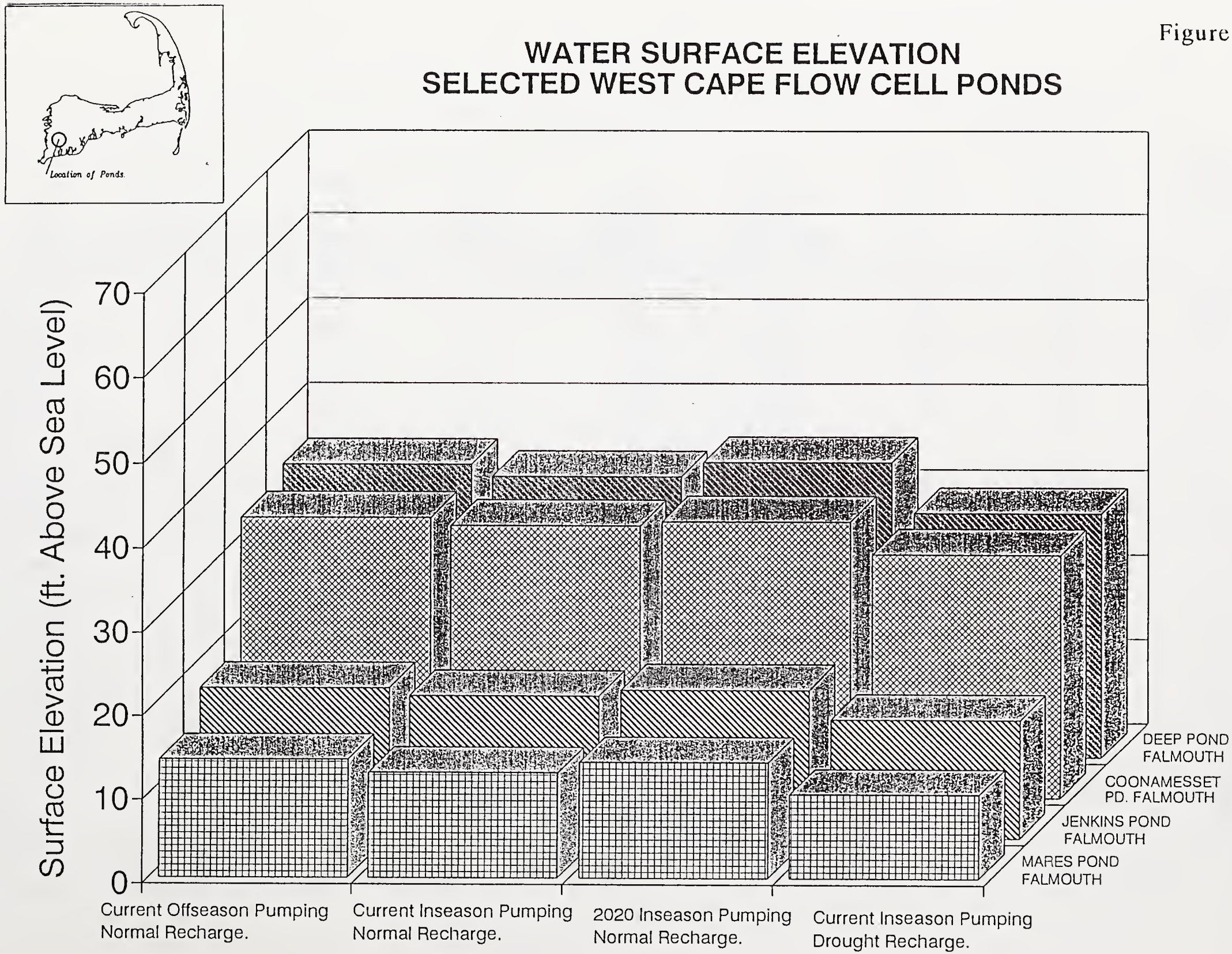
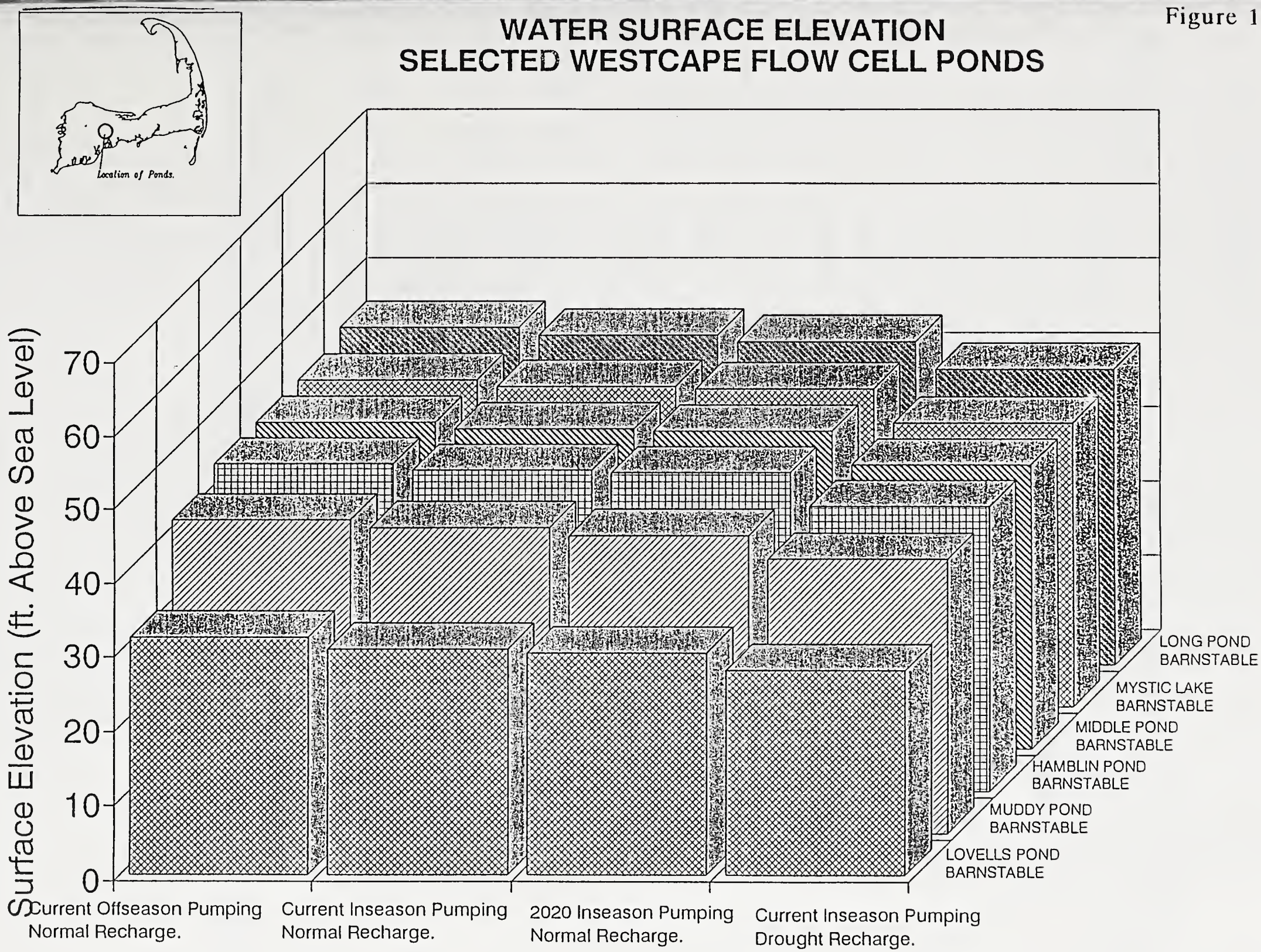

WATER SURFACE ELEVATION
SELECTED WEST CAPE FLOW CELL PONDS
Location of Ponds.
Surface Elevation (ft. Above Sea Level)
70
60
50
40
30
20
10
0
DEEP POND FALMOUTH
COONAMESSET PD. FALMOUTH
JENKINS POND FALMOUTH
MARES POND FALMOUTH
Current Offseason Pumping Normal Recharge.
Current Inseason Pumping Normal Recharge.
2020 Inseason Pumping Normal Recharge.
Current Inseason Pumping Drought Recharge.

Figure 19

# WATER SURFACE ELEVATION
# SELECTED WESTCAPE FLOW CELL PONDS



2. East Cape Flow Cell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**The East Cape Flow Cell** (Monomoy Lens) lies to the east of the West Cape cell and extends from the Bass River to the Town Cove-Boat Meadow River system located near the Orleans/Eastham town line. The East Cape flow cell is the second largest of the five potable flow cells and provides drinking water for the towns of Brewster, Dennis, Harwich, Chatham, and Orleans. The East Cape flow cell also contains several streams that are the sites of ground water discharge, and several large ponds and lakes. The water table elevation ranges from nearly sea level at the shoreline to about forty feet above sea level at the center of the flow cell. The land surface overlying the cell is approximately nine miles from north to south and 16 miles from east to west. Its southern and eastern borders are Nantucket Sound and the Atlantic Ocean. The northern border is Cape Cod Bay except for the northern section bounded by the Eastham Flow cell. Its western edge is the Bass River and Chase Garden Creek.

**Table 17**
**East Cape Flow Cell Pumping Summary**
million gallons per day

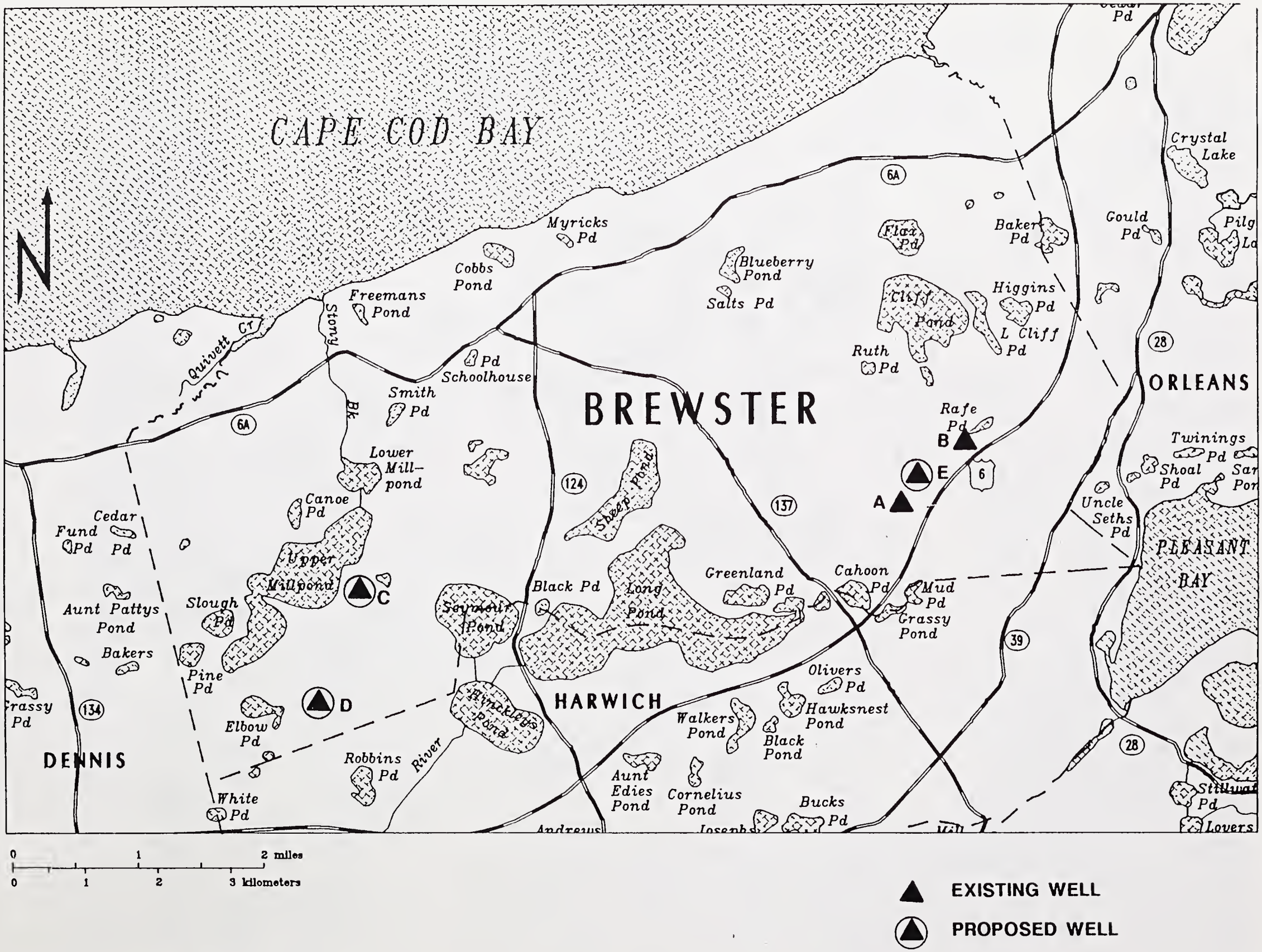
| Community | Map Symbol | 1989 In-Season Pumpage | 1989 Off-Season pumpage | Projected 2020 In-Season Pumpage | Projected 2020 Off-Season Pumpage | Pumping Capacity |
|---|---|---|---|---|---|---|
| Orleans | A-G | 1.64 | 0.80 | 2.82 | 1.55 | 5.92 |
| Dennis | A-Q | 4.71 | 1.86 | 5.26 | 2.39 | 13.15 |
| Brewster | A-E | 1.75 | 0.80 | 2.29 | 1.34 | 8.10 |
| Chatham | A-G | 1.39 | 0.66 | 1.77 | 0.91 | 6.84 |
| Harwich | A-K | 3.08 | 1.23 | 3.56 | 1.52 | 12.00 |
| Yarmouth | T-U | --- | --- | 1.39 | 0.54 | 2.09 |
| TOTAL | | 12.57 | 5.35 | 17.09 | 8.25 | 48.1 |

DEM Office of Water Resources

CAPE COD BAY
EASTHAM
Boat Meadow R
Rock Hbr Cr
Icehouse Pond
ATLANTIC OCEAN
Cedar Pd
ORLEANS
6A
Crystal Lake
BREWSTER
6
Flax Pd
Baker Pd
Gould Pd
B
A
Pilgrim Lake
E
Higgins Pd
Cliff Pond
C
D
G
28
L Cliff Pd
Rafe Pd
F
Twinings Pd
Shoal Pd
Sarahs Pond
PLEASANT BAY
Uncle Seths Pd
39
Mud Pd
HARWICH
Grassy Pond
0
1
2 miles
0
1
2
3 kilometers
EXISTING WELL
PROPOSED WELL

CAPE COD BAY
N
Scargo Lake
BREWSTER
Canoe Pd
Cedar Pd
Fund Pd
Upper Millpond
Aunt Pattys Pond
Slough Pd
Pine Pd
Chase Garden Cr
Quivett Cr
Stony Bk
Flax Pd
Run Pd
Grassy Pd
Elbow Pd
Matthews Pond
DENNIS
White Pd
Rob
Follins Pond
Mill Pd
Howes Pd
Miller Pd
Perch Pd
Elishas Pd
Thatchers Pond
Greenough Pond
Dinahs Pond
Eagle Pond
Herring
Sand
YARMOUTH
Flax Pd
Fresh Pd
Swan Pd
HARWICH
Labans Pd
Plashes Pd
Long Pond
Pond R
Bassetts Lot Pd
Horse Pd
Big Sandy Pd
Jabinettes Pond
Parkers Seine R
Kelleys Pond
Swan
Uncle Stephans Pd
NANTUCKET SOUND
0 1 2 miles
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

Figure 22


CAPE COD BAY
N
BREWSTER
HARWICH
DENNIS
ORLEANS
PLEASANT BAY
Crystal Lake
Gould Pd
Baker Pd
Flax Pd
Blueberry Pond
Salts Pd
Cliff Pond
Higgins Pd
L Cliff Pd
Ruth Pd
Rafe Pd
Myricks Pd
Cobbs Pond
Freemans Pond
Stony Bk
Quivett Cr
Pd Schoolhouse
Smith Pd
Lower Millpond
Canoe Pd
Upper Millpond
Sheep Pond
Cedar Fund Pd
Aunt Pattys Pond
Slough Pd
Bakers
Pine Pd
Seymour Pond
Black Pd
Long Pond
Greenland Pd
Cahoon Pd
Mud Pd
Grassy Pond
Twinings Pd
Shoal Pd
Uncle Seths Pd
Olivers Pd
Hawksnest Pond
Walkers Pond
Black Pond
Aunt Edies Pond
Cornelius Pond
Bucks Pd
Elbow Pd
Robbins Pd
White Pd
River
Stillwater Pd
Lovers
Grassy Pd
A
B
C
D
E
6A
6
28
124
137
39
134
0 1 2 mile
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

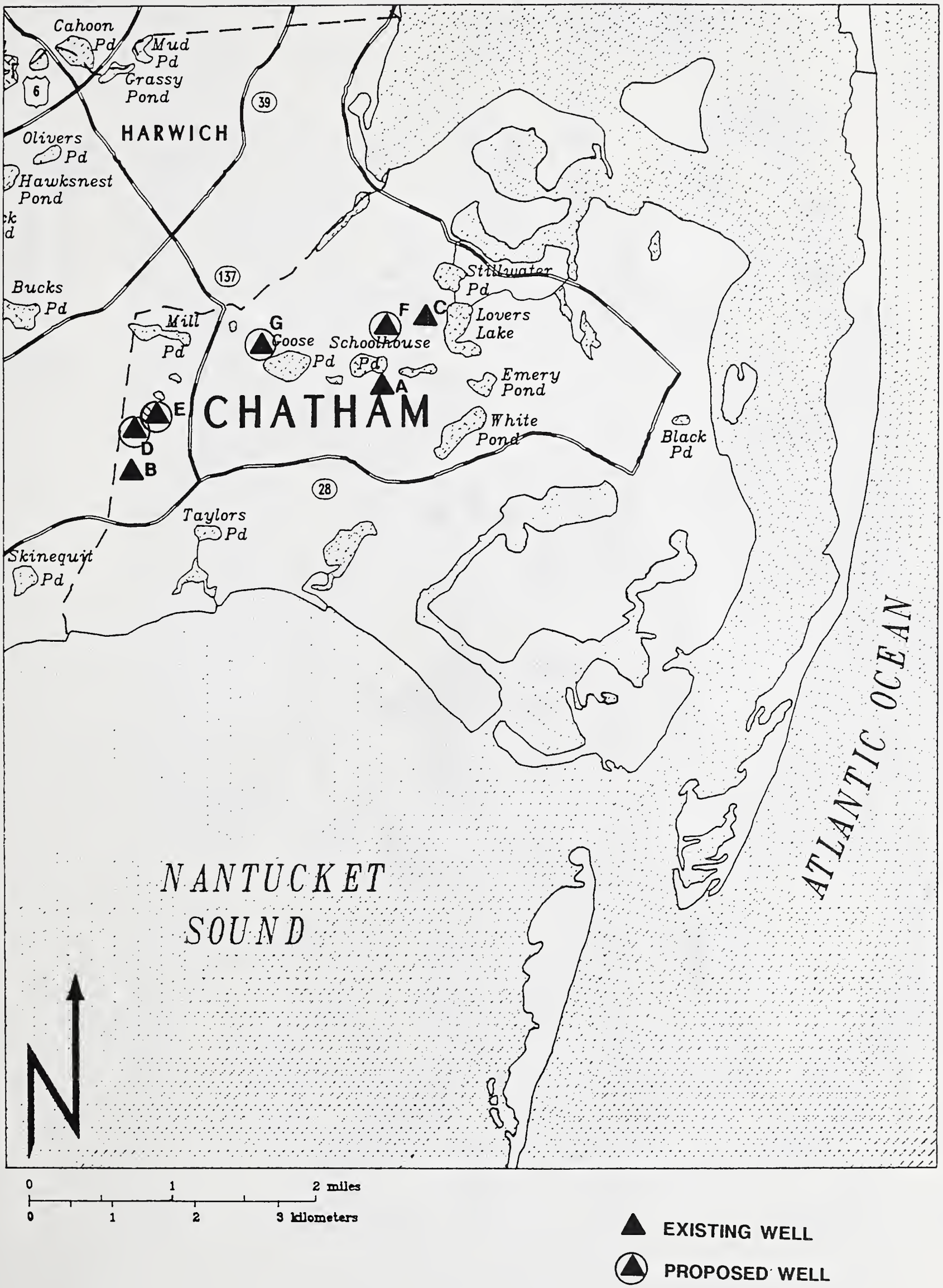

Cahoon Pd
Mud Pd
Grassy Pond
6
39
HARWICH
Olivers Pd
Hawksnest Pond
Bucks Pd
137
Mill Pd
G
Goose Pd
F
C
Schoolhouse Pd
Stillwater Pd
Lovers Lake
Emery Pond
A
E
D
B
CHATHAM
White Pond
Black Pd
28
Taylors Pd
Skinequit Pd
NANTUCKET SOUND
ATLANTIC OCEAN
N
0 1 2 miles
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

Figure 24

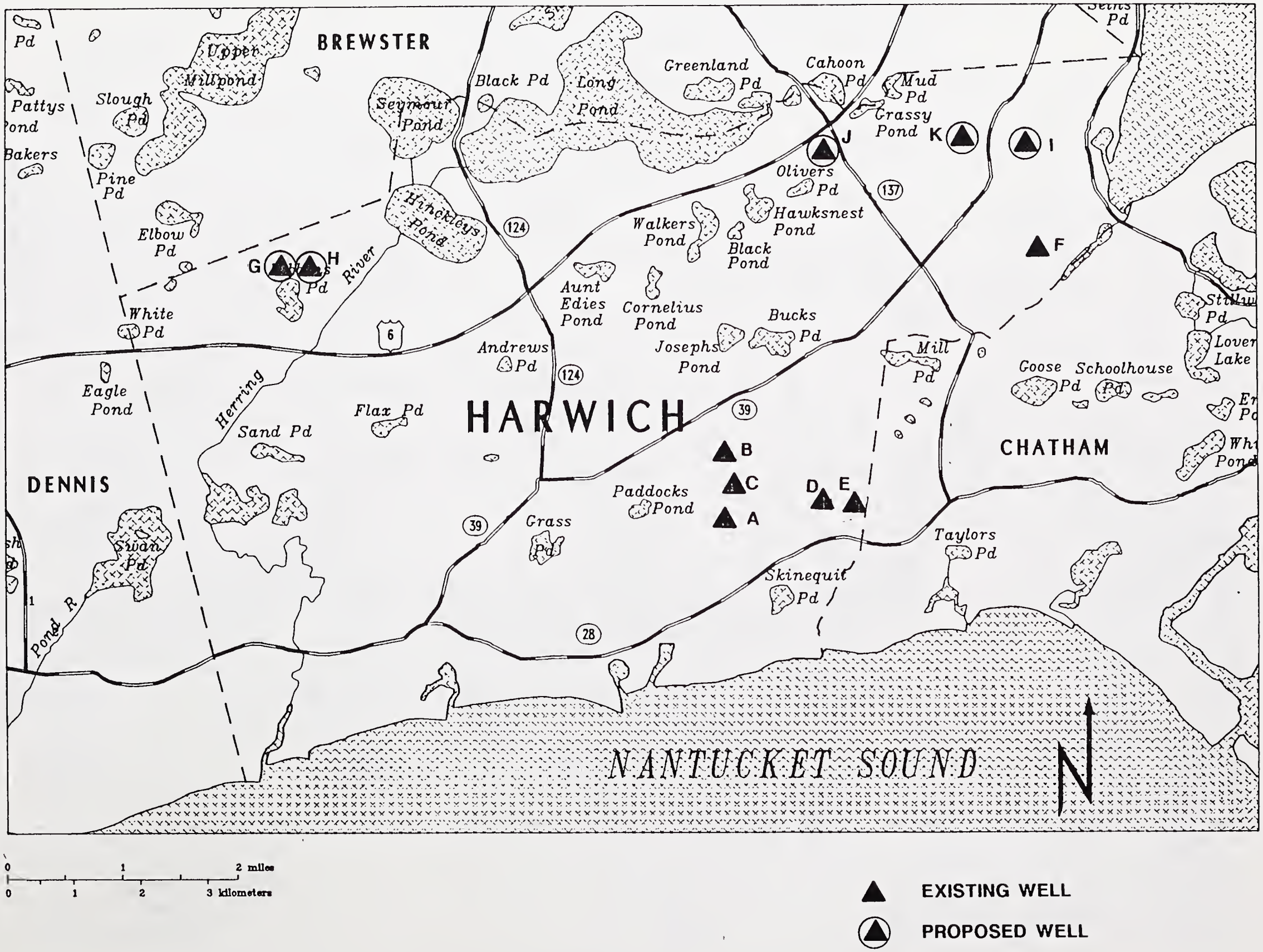
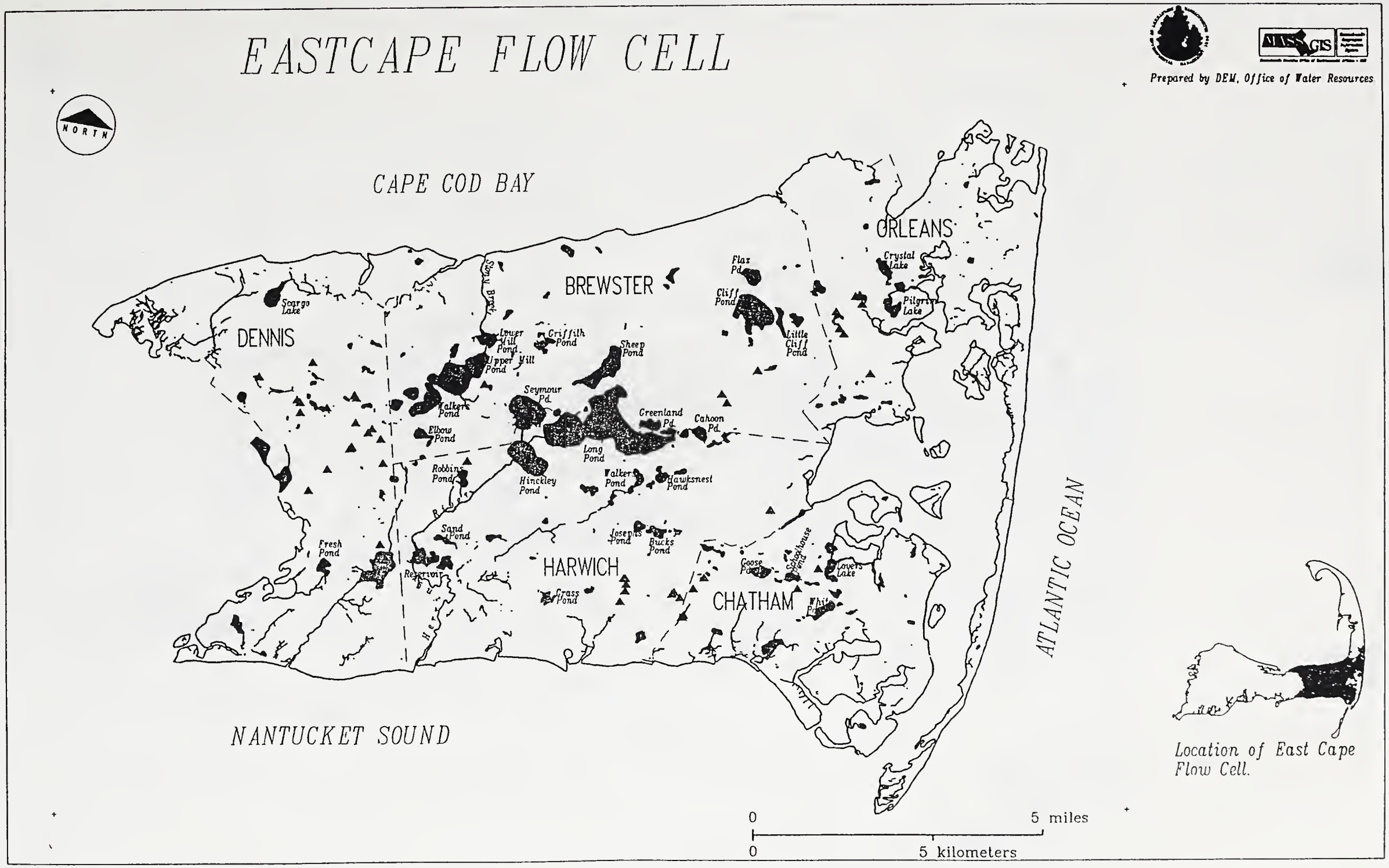

BREWSTER
HARWICH
DENNIS
CHATHAM
NANTUCKET SOUND
N
Upper Millpond
Slough Pd
Pattys Pond
Bakers
Pine Pd
Elbow Pd
White Pd
Eagle Pond
Herring
Sand Pd
Flax Pd
Seymour Pond
Hinckleys Pond
River
Black Pd
Long Pond
Greenland Pd
Cahoon Pd
Mud Pd
Grassy Pond
Olivers Pd
Hawksnest Pond
Walkers Pond
Black Pond
Aunt Edies Pond
Cornelius Pond
Bucks Pd
Josephs Pond
Andrews Pd
Mill Pd
Goose Pd
Schoolhouse Pd
Lover Lake
Paddocks Pond
Grass Pd
Taylors Pd
Skinequit Pd
Swan Pd
Pond R
G
H
J
K
I
F
B
C
A
D
E
124
137
6
39
28
0 1 2 mile
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

Figure 25

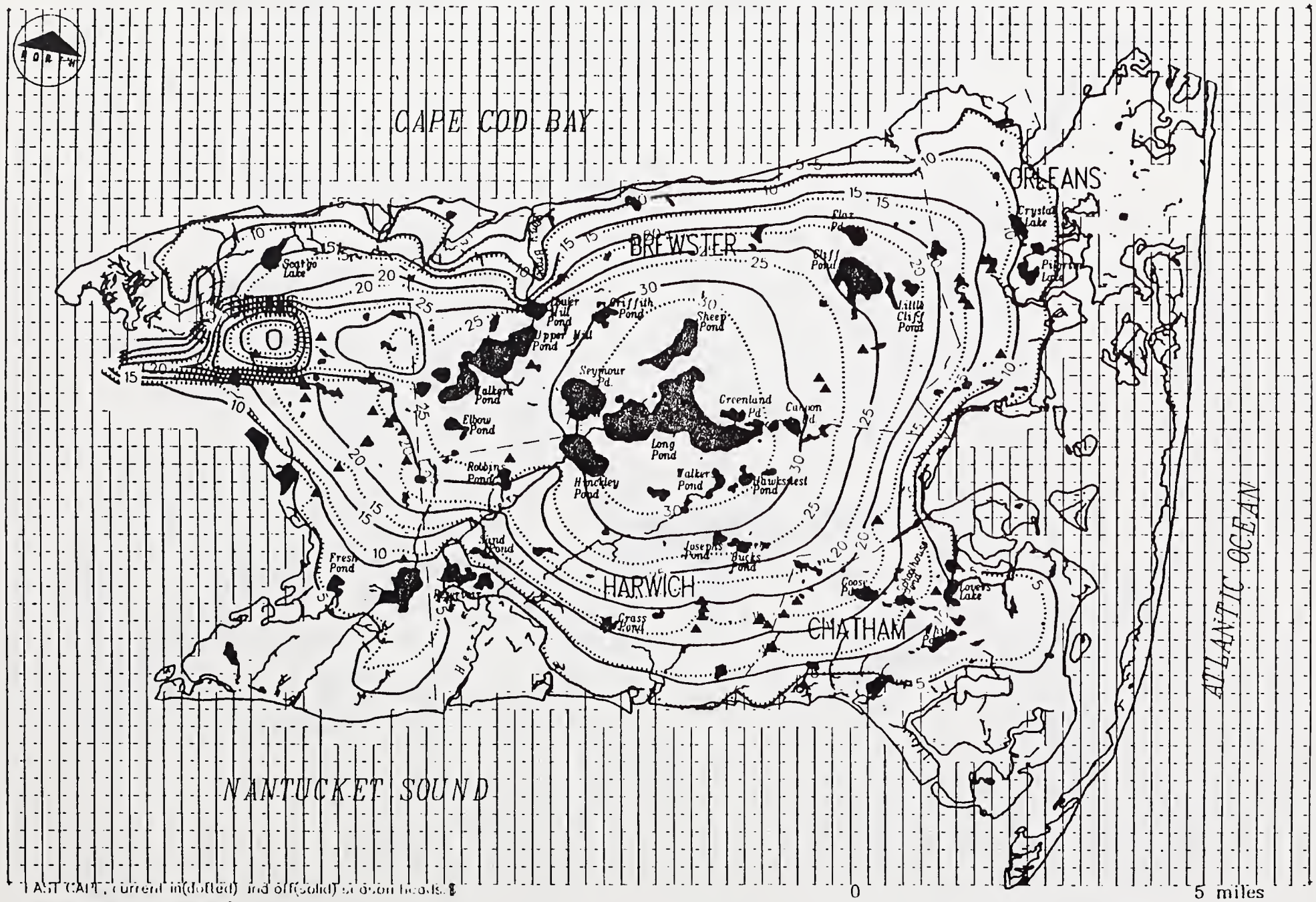



LAKES, PONDS AND STREAMS MODELED IN EAST CAPE FLOW CELL

# EASTCAPE FLOW CELL

Prepared by DEM, Office of Water Resources.

Figure 26




EAST CAPE, current in(dotted) and off(solid) season heads. normal recharge simulation.

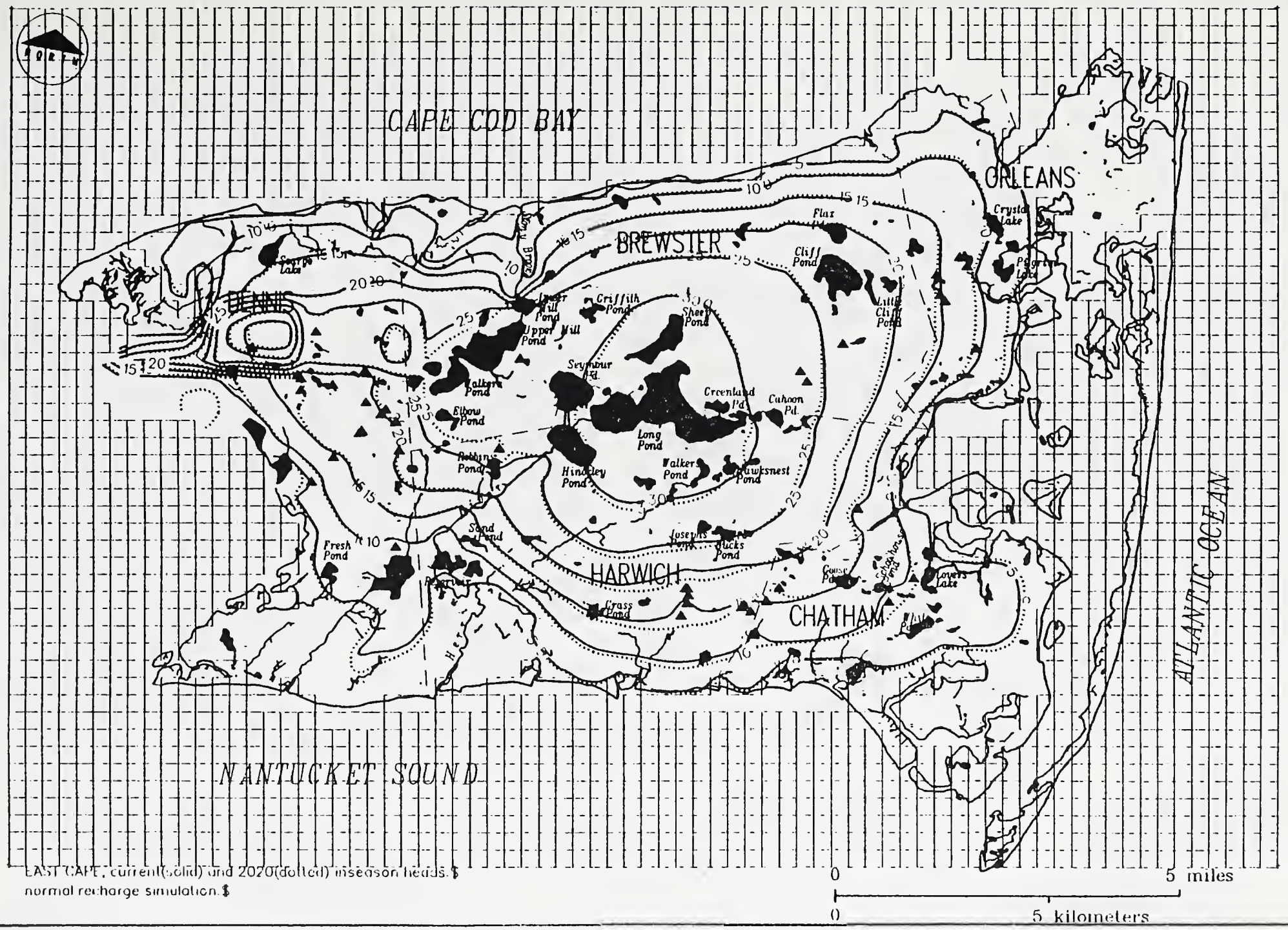
*Location of East Cape Flow Cell.*

**Heads Resulting From Current Off-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (dotted line)**

# EASTCAPE FLOW CELL

Prepared by DEM, Office of Water Resources.

Figure 27



*Location of East Cape Flow Cell.*

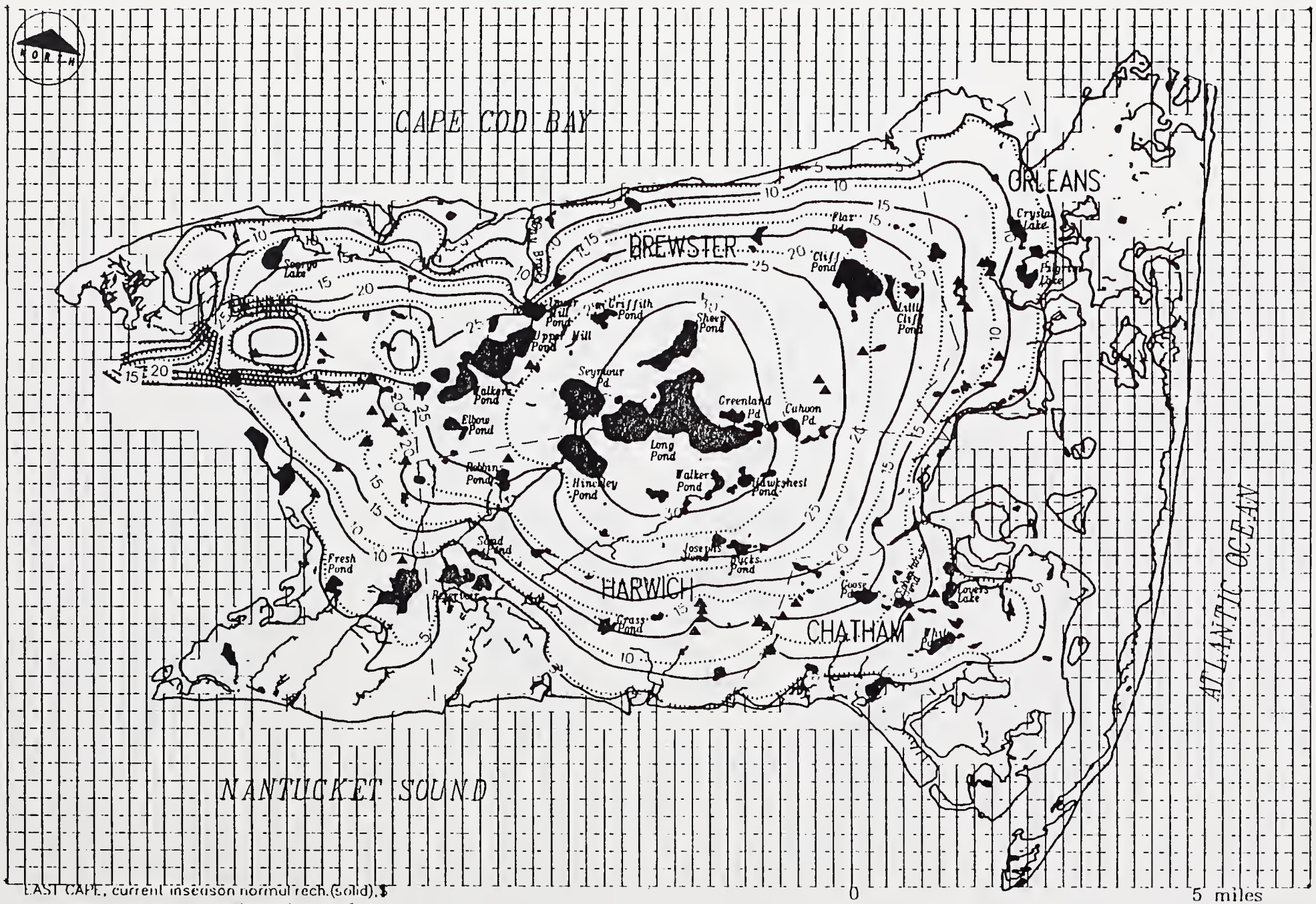
EAST CAPE, current(solid) and 2020(dotted) inseason heads.$
normal recharge simulation.$

**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Proposed 2020 In-Season Pumping Under Normal Recharge Conditions (dotted line)**

# EASTCAPE FLOW CELL

Prepared by DEM, Office of Water Resources.

Figure 28




EAST CAPE, current inseason normal rech.(solid), and current inseason drought(dotted) heads.

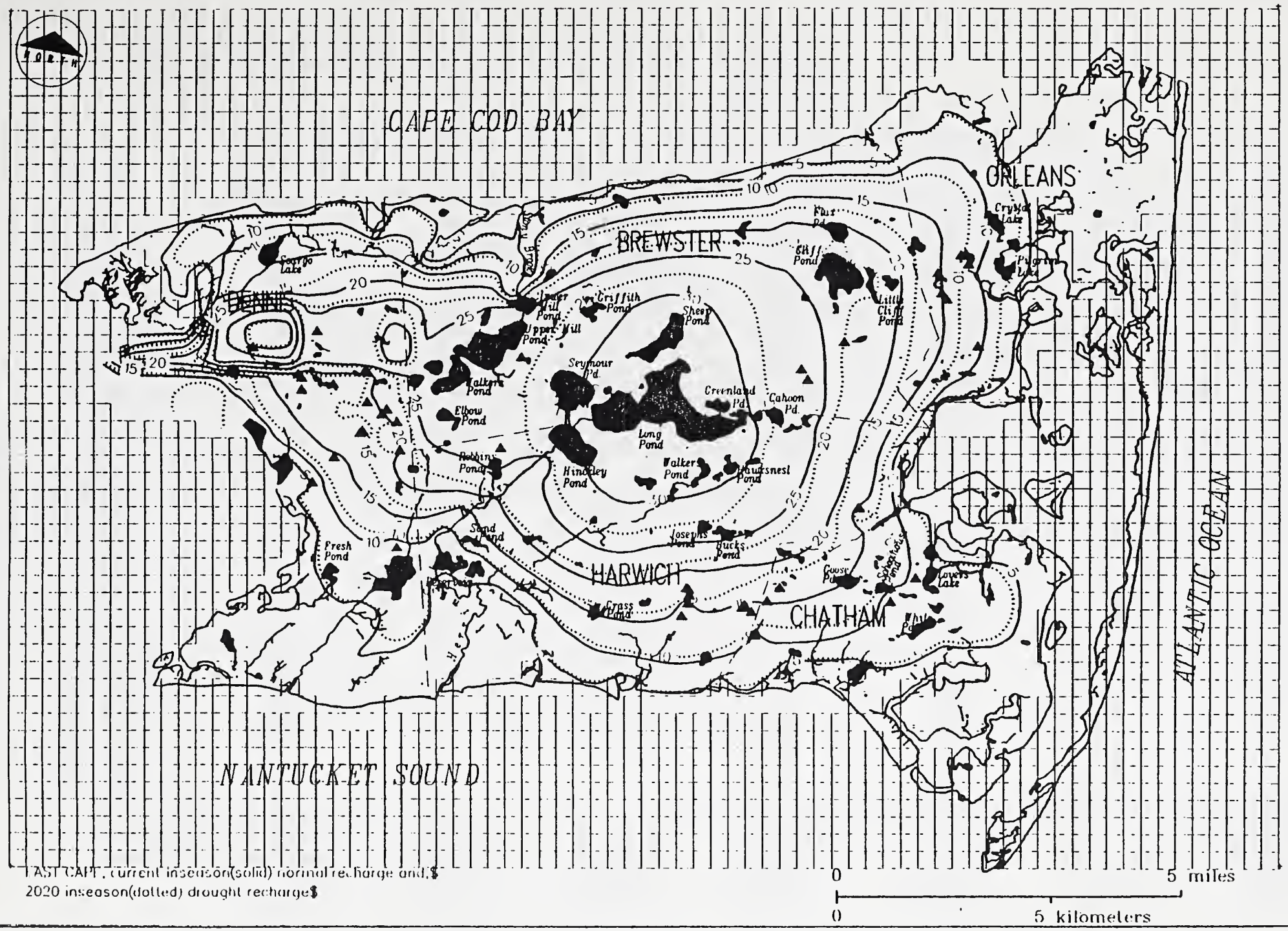
*Location of East Cape Flow Cell.*

**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Current In-Season Pumping Under Drought Recharge Conditions (dotted line)**

# EASTCAPE FLOW CELL

Prepared by DEM, Office of Water Resources.

Figure 29



*Location of East Cape Flow Cell.*

**Heads Resulting From Current In-Season Pumping Under Normal Recharge Conditions (solid line) and Heads Resulting From Proposed 2020 In-Season Pumping Under Drought Conditions (dotted line)**

# Table 18

Calculated Pond Levels[1] for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in feet above NGVD*
East Cape Flow Cell

| Pond Name | Pond Levels During Existing Inseason Pumpage Under Average Recharge Conditions | Pond Levels During 2020 Inseason Pumpage Under Average Recharge Conditions | Pond Levels During Existing Offseason Pumpage Under Average Recharge Conditions | Pond Levels During 2020 Offseason Pumpage Under Average Recharge Conditions | Pond Levels During Existing Inseason Pumpage Under Drought Recharge Conditions | Pond Levels During 2020 Inseason Pumpage Under Drought Recharge Conditions | Pond Levels During Existing Offseason Pumpage Under Drought Recharge Conditions | Pond Levels During 2020 Offseason Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| BREWSTER | | | | | | | | |
| Cliff Pond | 23.29 | 23.35 | 24.13 | 24.16 | 20.28 | 20.30 | 21.05 | 21.05 |
| Elbow Pond | 26.43 | 25.70 | 27.53 | 26.89 | 23.94 | 23.15 | 24.91 | 24.21 |
| Cahoon Pond | 28.37 | 28.25 | 30.47 | 30.24 | 25.15 | 24.96 | 26.99 | 26.69 |
| Flax Pond | 23.27 | 23.34 | 24.12 | 24.16 | 20.27 | 20.29 | 21.05 | 21.04 |
| Greenland Pond | 31.47 | 31.35 | 32.45 | 32.33 | 28.51 | 28.34 | 29.39 | 29.22 |
| Griffith Pond | 28.96 | 28.79 | 30.53 | 30.36 | 26.30 | 26.08 | 27.64 | 27.42 |
| Little Cliff Pond | 23.26 | 23.32 | 24.10 | 24.13 | 20.25 | 20.26 | 21.03 | 21.01 |
| Upper Mill Pond | 26.50 | 25.81 | 27.46 | 26.84 | 24.06 | 23.31 | 24.89 | 24.21 |
| Lower Mill Pond | 26.24 | 25.61 | 27.16 | 26.59 | 23.82 | 23.14 | 24.62 | 24.00 |
| Seymour Pond | 29.88 | 29.61 | 30.70 | 30.46 | 27.57 | 27.25 | 28.29 | 28.00 |
| Sheep Pond | 31.38 | 31.29 | 32.35 | 32.26 | 28.48 | 28.34 | 29.34 | 29.20 |
| Walkers Pond | 26.49 | 25.77 | 27.52 | 26.89 | 24.01 | 23.24 | 24.91 | 24.22 |
| CHATHAM | | | | | | | | |
| Goose Pond | 16.16 | 15.91 | 16.40 | 16.48 | 12.81 | 13.30 | 13.78 | 13.79 |
| Lover's Lake | 8.71 | 8.97 | 10.19 | 10.63 | 7.53 | 7.40 | 8.39 | 8.78 |
| School House Pd | 11.60 | 11.80 | 12.54 | 13.13 | 8.67 | 9.76 | 10.33 | 10.86 |
| White Pond | 7.65 | 8.29 | 8.57 | 9.11 | 6.29 | 6.88 | 7.05 | 7.54 |
| DENNIS | | | | | | | | |
| Fresh Pond | 5.83 | 5.93 | 6.31 | 6.40 | 5.29 | 5.38 | 5.65 | 5.72 |
| Scargo Lake | 14.65 | 14.55 | 15.34 | 15.24 | 12.46 | 12.30 | 13.04 | 12.88 |
| HARWICH | | | | | | | | |
| Long Pond | 31.47 | 31.37 | 32.34 | 32.24 | 28.62 | 28.46 | 29.39 | 29.24 |
| Bucks Pond | 27.03 | 27.53 | 28.15 | 28.59 | 23.72 | 24.15 | 24.66 | 25.03 |
| Grass Pond | 14.69 | 15.42 | 15.34 | 16.02 | 12.88 | 13.57 | 13.40 | 14.03 |
| Hawks Nest Pond | 31.08 | 30.84 | 32.07 | 31.86 | 27.86 | 27.54 | 28.72 | 28.45 |
| Hinckley Pond | 29.70 | 29.48 | 30.46 | 30.25 | 27.54 | 27.28 | 28.19 | 27.95 |
| Joseph's Pond | 26.70 | 27.37 | 28.69 | 29.24 | 23.45 | 24.06 | 25.13 | 25.62 |
| Reservoir | 7.54 | 7.56 | 7.91 | 7.93 | 7.25 | 7.26 | 7.55 | 7.56 |
| Sand Pond | 11.93 | 12.05 | 13.12 | 13.22 | 11.45 | 11.55 | 12.39 | 12.47 |
| Robbins Pond | 26.04 | 25.28 | 26.67 | 25.99 | 24.56 | 23.77 | 25.09 | 24.38 |
| Walkers Pond | 31.26 | 31.23 | 32.84 | 32.82 | 28.14 | 28.07 | 29.51 | 29.44 |
| ORLEANS | | | | | | | | |
| Crystal Lake | 8.71 | 8.54 | 9.29 | 9.11 | 7.38 | 7.15 | 7.86 | 7.63 |
| Pilgrim Lake | 7.44 | 6.72 | 8.13 | 7.48 | 6.24 | 5.47 | 6.82 | 6.12 |

1. Calculated Pond levels are relative rather than absolute. Actual Pond levels may vary.

* National Geodetic Vertical Datum

# Table 19

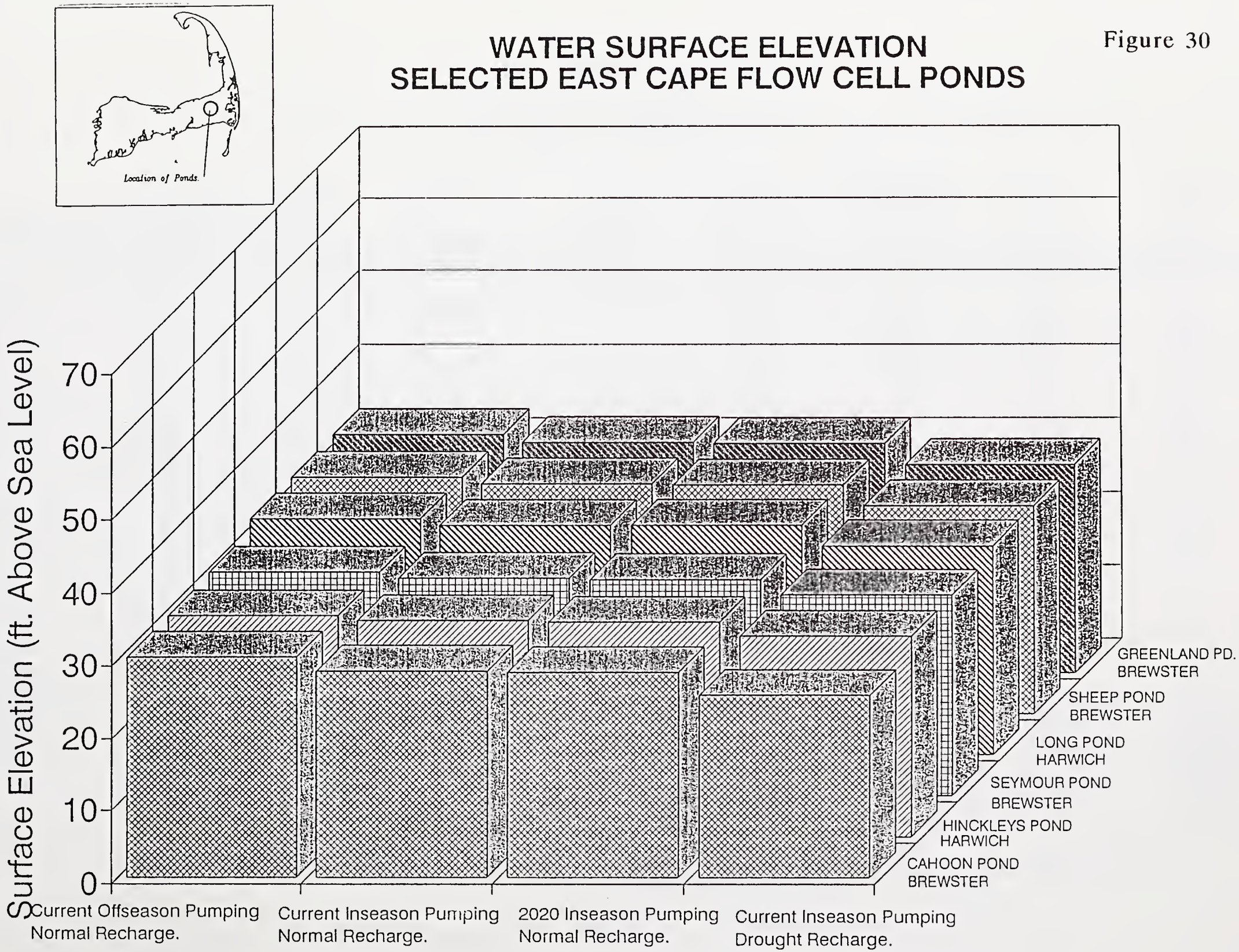
Calculated Streamflows[1] for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in cubic feet per second
East Cape Flow Cell

| River System | Streamflow During Existing Inseason Pumpage Under Average Recharge Conditions | Streamflow During 2020 Inseason Pumpage Under Average Recharge Conditions | Streamflow During Existing Offseason Pumpage Under Average Recharge Conditions | Streamflow During 2020 Offseason Pumpage Under Average Recharge Conditions | Streamflow During Existing Inseason Pumpage Under Drought Recharge Conditions | Streamflow During 2020 Inseason Pumpage Under Drought Recharge Conditions | Streamflow During Existing Offseason Pumpage Under Drought Recharge Conditions | Streamflow During 2020 Offseason Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| Herring River (Harwich) | 5.36 | 5.05 | 8.19 | 7.93 | 3.12 | 2.78 | 5.34 | 5.02 |
| Stoney Brook (Brewster) | 3.78 | 3.72 | 4.61 | 4.54 | 3.15 | 3.07 | 3.82 | 3.74 |

[1] Calculated streamflows are relative rather than absolute. Due to an artifact of the model associated with wastewater flows, streamflows under 2020 pumpage conditions may not in reality be greater than those under existing conditions as indicated. However the model does indicate that streamflows do not significantly change due to increases in pumping in 2020.

Figure 30

# WATER SURFACE ELEVATION
# SELECTED EAST CAPE FLOW CELL PONDS



## 3. Wellfleet Flow Cell


| Table/Figure | Description | Page |
|---|---|---|
| Table 20 | Wellfleet Flow Cell pumping summary | 75 |
| Table 21 | Calculated Pond Levels for existing and proposed pumping during average and drought recharge conditions | 80 |
| Table 22 | Calculated streamflows for existing and proposed pumping during average and drought recharge conditions | 81 |
| Figure 31 | Wellfleet public water supply wells | 76 |
| Figure 32 | Steady state: Average pumping and in-season pumping heads under normal recharge conditions | 77 |
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| Figure 35 | Water surface elevations for selected Wellfleet flow cell ponds | 82 |


**The Wellfleet flow cell** (Chequesset Lens), to the north of the Eastham Cell, extends approximately three-quarters of a mile to three miles across at its widest point and is approximately six miles long. Approximately two-thirds of Wellfleet and the southern one-third of Truro are included in this cell. The eastern border is the Atlantic Ocean and its western border is Cape Cod Bay. The southern edge extends to Blackfish Creek, south of Lecount Hollow Road in Wellfleet. The northern edge extends to the Pamet River in Truro. The flow cell currently has no public water supply systems, however it is projected that several public water supply wells may be in operation in the future (Table 20). Water table elevations range from sea level to approximately eight feet above sea level in the Wellfleet flow cell.

**Table 20**
**Wellfleet Flow Cell Pumping Summary**
million gallons per day

| Community | Map Symbol | 1989 In-Season Pumpage | 1989 Off-Season Pumpage | Projected 2020 In-Season Pumpage | Projected 2020 Off-Season Pumpage | Pumping Capacity |
|---|---|---|---|---|---|---|
| Provincetown | F | --- | --- | 0.80 | 0.20 | 0.80 |
| Wellfleet | G | --- | --- | 0.75 | 0.30 | 0.75 |
| TOTAL | | --- | --- | 1.55 | 0.50 | 1.55 |

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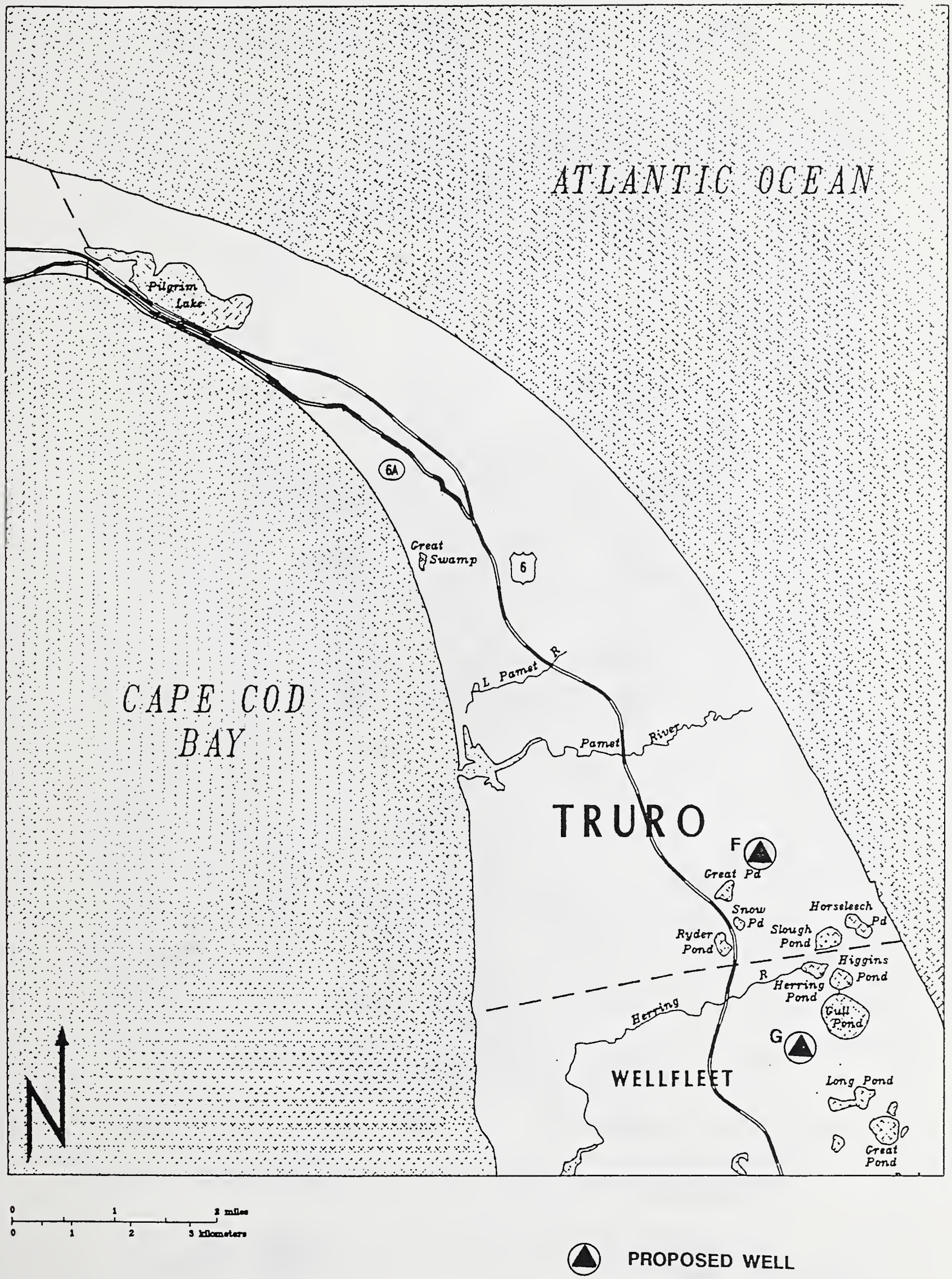
4. The Eastham Flow Cell

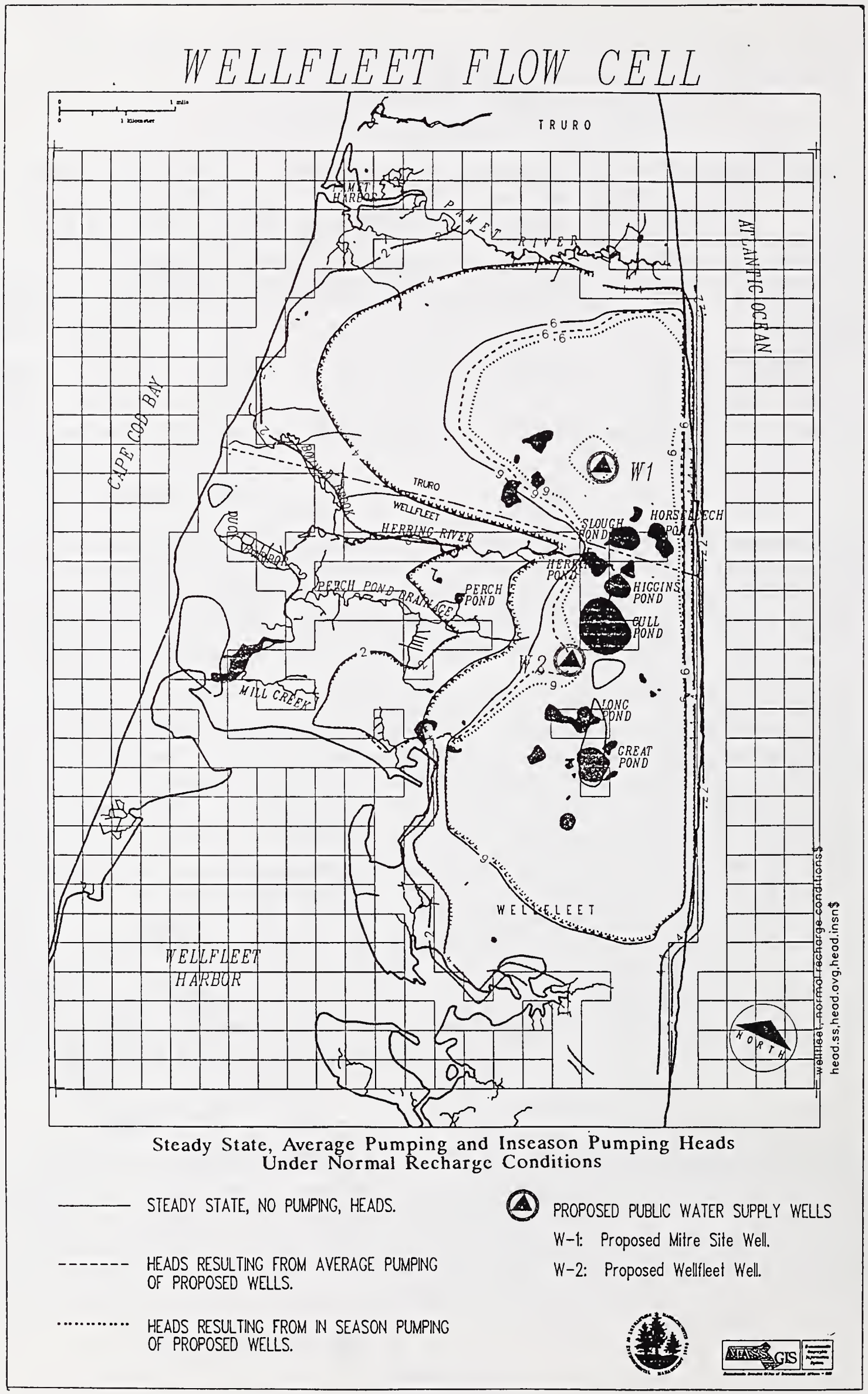
Located to the northeast of the East Cape cell and extending from the Town Cove-Boat Meadow River system near the Orleans/Eastham border to Blackfish Creek in Wellfleet, the land surface of the cell is approximately three miles wide and seven miles long. The cell includes most of Eastham and the lower portion of Wellfleet. It is bordered to the east by the Atlantic Ocean and the west by Cape Cod Bay.

The Eastham flow cell is much smaller than the West and East Cape flow cells and has no existing public water supply systems. However, there is potential for development of public water supply in the future. Domestic and industrial water needs are met by small capacity private wells tapping the flow cell. Water table elevations range from sea level to approximately 18 feet above sea level. Maximum water table elevations are greater in the Eastham flow cell than might be expected because of the presence within the flow system of a thick (greater than 300 feet) deposit of fine-grained sediment of very low permeability, which underlies a thinner deposit of coarse-grained sand and gravel. There were no model simulations performed on the Eastham flow cell because of the absence of artificial stress (large pumping wells) at the time the analysis was performed. Due to increasing water quality problems in private wells in Eastham, however, the Lower Cape Water Supply Task Force currently is working to identify solutions for water supply needs, which may include additional wells. Future modeling efforts should therefore include water supply sources proposed to meet 2020 Eastham demands.

5. The Provincetown Flow Cell

The cell, which extends from Pilgrim Lake in Truro to the end of the Cape Cod peninsula, is not used for public supplies because hydrogen sulfide and iron are present in much of the flow cell where sand dunes have covered marsh deposits. Water table elevations range from sea level at the coast to a maximum of five feet above sea level in the middle of the flow cell. The cell is approximately three miles wide at the widest point and seven miles long. The southeastern border is located near Pilgrim Lake/Salt Meadow.


ATLANTIC OCEAN
Pilgrim Lake
6A
Great Swamp
6
L Pamet R
Pamet River
CAPE COD BAY
TRURO
F
Great Pd
Snow Pd
Horseleech Pd
Slough Pond
Ryder Pond
Higgins Pond
R
Herring Pond
Herring
Gull Pond
G
WELLFLEET
Long Pond
Great Pond
N
0 1 2 miles
0 1 2 3 kilometers
PROPOSED WELL




Steady State, Average Pumping and Inseason Pumping Heads
Under Normal Recharge Conditions

——— STEADY STATE, NO PUMPING, HEADS.

------- HEADS RESULTING FROM AVERAGE PUMPING OF PROPOSED WELLS.

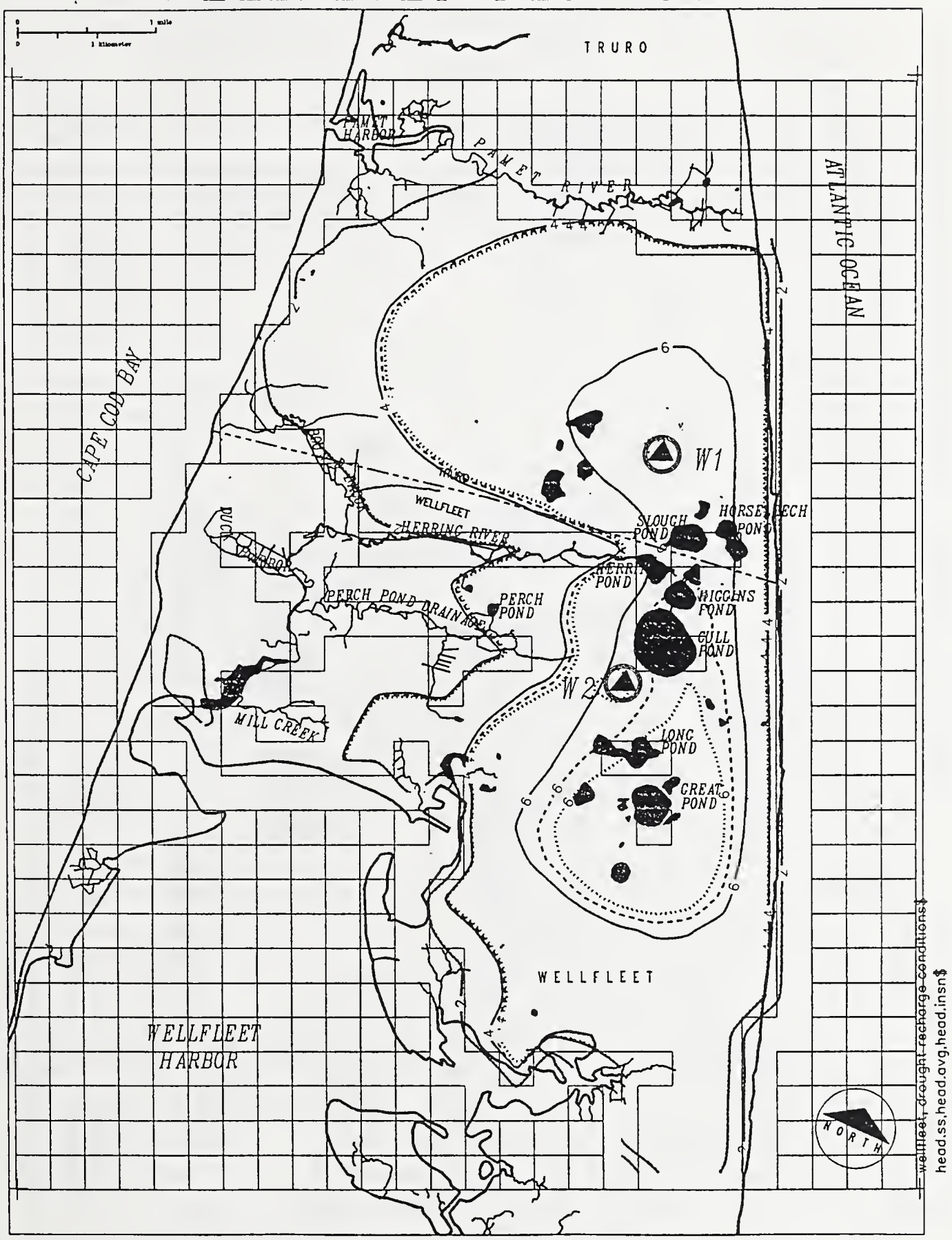
····· HEADS RESULTING FROM IN SEASON PUMPING OF PROPOSED WELLS.

PROPOSED PUBLIC WATER SUPPLY WELLS

W-1: Proposed Mitre Site Well.

W-2: Proposed Wellfleet Well.

# WELLFLEET FLOW CELL




**Steady State, Average Pumping and Inseason Pumping Heads Under Drought Conditions**

——— STEADY STATE, NO PUMPING, HEADS.

------- HEADS RESULTING FROM AVERAGE PUMPING OF PROPOSED WELLS.

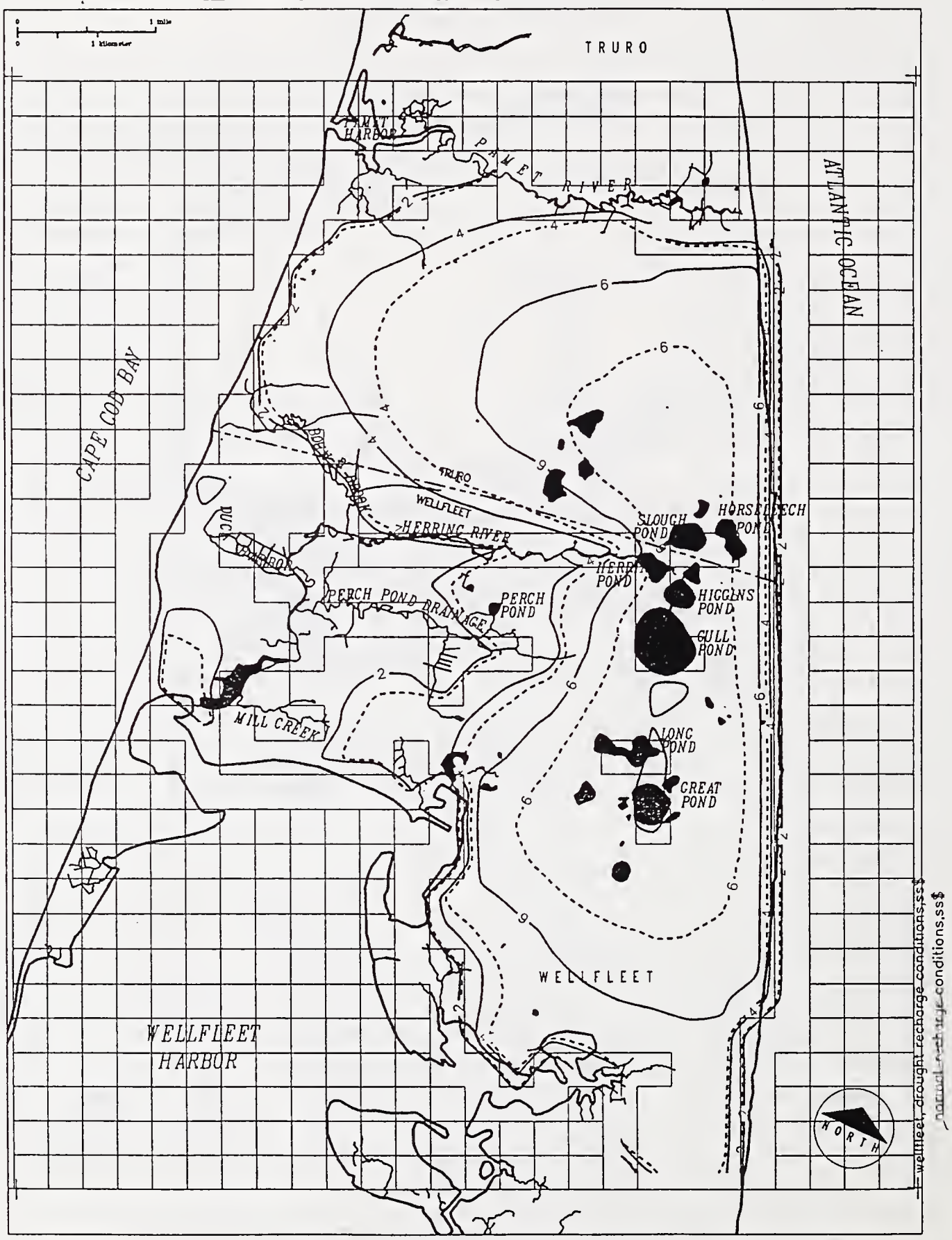
····· HEADS RESULTING FROM IN SEASON PUMPING OF PROPOSED WELLS.

PROPOSED PUBLIC WATER SUPPLY WELLS

W-1: Proposed Mitre Site Well.

W-2: Proposed Wellfleet Well.

# WELLFLEET FLOW CELL




Steady State Heads Under Normal Precipitation and Drought Conditions

——— STEADY STATE HEADS UNDER NORMAL PRECIPITATION CONDITIONS

------- STEADY STATE HEADS UNDER DROUGHT CONDITIONS

# Table 21

Calculated Pond Levels for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in feet above NGVD*
Wellfleet Flow Cell**

| Pond Name | Pond Levels Under Average Recharge Conditions; No Water Supply Withdrawals | Pond Levels During Hypothetical Existing Average Annual Pumpage Under Average Recharge Conditions | Pond Levels During Hypothetical Existing Inseason Annual Pumpage Under Average Recharge Conditions | Pond Levels During Proposed 2020 Inseason Annual Pumpage Under Average Recharge Conditions | Pond Levels Under Drought Recharge Conditions; No Water Supply Withdrawals | Pond Levels During Hypothetical Existing Average Annual Pumpage Under Drought Recharge Conditions | Pond Levels During Hypothetical Existing Inseason Annual Pumpage Under Drought Recharge Conditions | Pond Levels During Proposed 2020 Inseason Annual Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| Slough Pond | 7.34 | 6.95 | 6.70 | 6.33 | 6.27 | 5.85 | 5.60 | 5.23 |
| Horse Leech Pond | 7.33 | 6.94 | 6.69 | 6.33 | 6.26 | 5.85 | 5.60 | 5.22 |
| Herring Pond | 7.27 | 6.88 | 6.63 | 6.28 | 6.24 | 5.83 | 5.57 | 5.21 |
| Higgins Pond | 7.69 | 7.22 | 6.94 | 6.52 | 6.60 | 6.09 | 5.78 | 5.36 |
| Gull Pond | 7.71 | 7.25 | 6.95 | 6.53 | 6.61 | 6.10 | 5.79 | 5.37 |
| Long Pond | 7.95 | 7.56 | 7.32 | 6.98 | 6.76 | 6.34 | 6.08 | 5.73 |
| Great Pond | 8.03 | 7.77 | 7.61 | 7.38 | 6.83 | 6.54 | 6.37 | 6.13 |

* National Geodetic Vertical Datum
** Seasonal data not simulated

# Table 22

Calculated Streamflow[1] for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in cubic feet per second
Wellfleet Flow Cell*

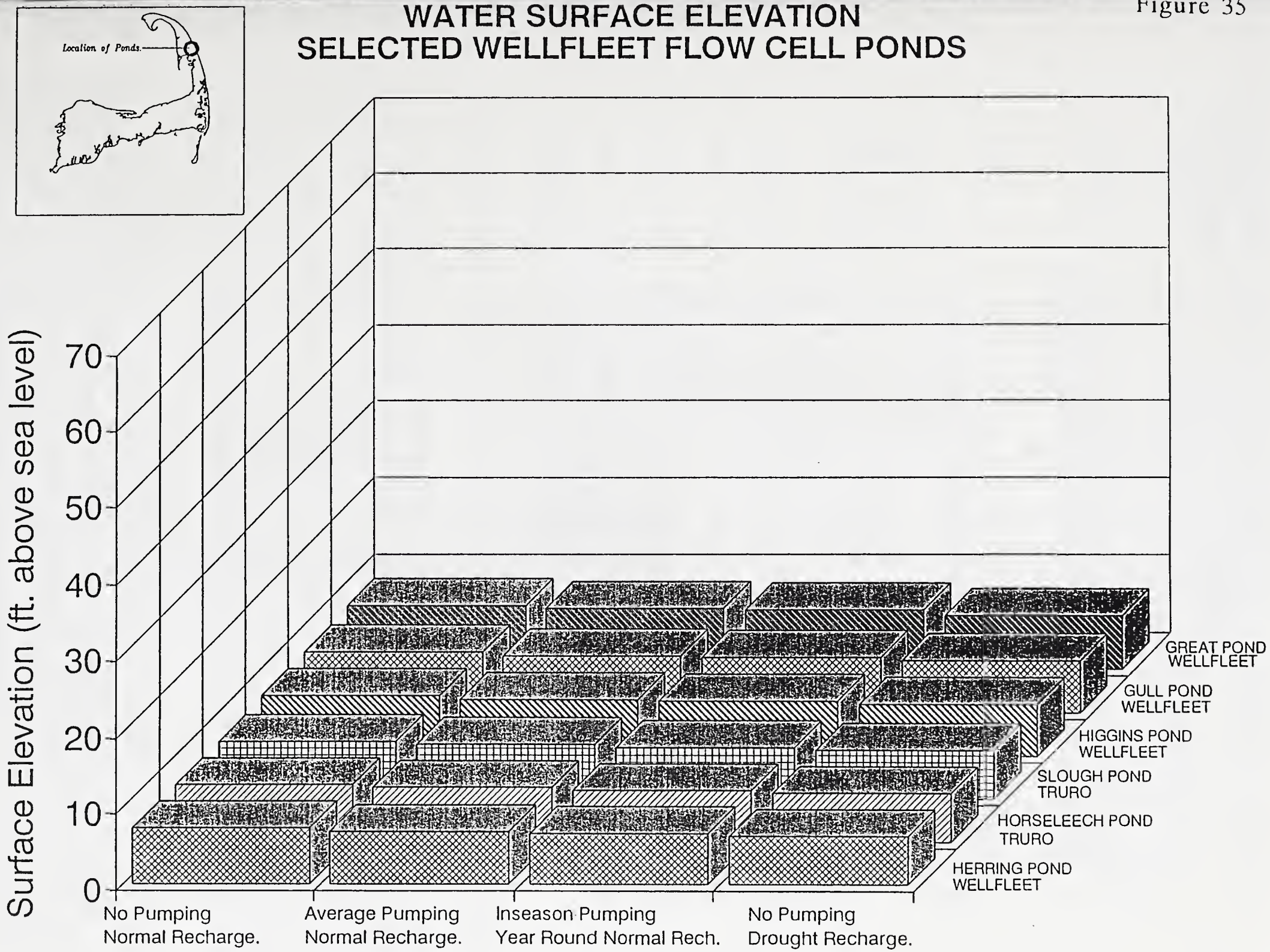
| River | Streamflow Under Average Recharge Conditions; No Water Supply Withdrawals | Streamflow During Hypothetical Existing Average Annual Pumpage Under Average Recharge Conditions | Streamflow During Hypothetical Existing Inseason Annual Pumpage Under Average Recharge Conditions | Streamflow During Proposed 2020 Inseason Annual Pumpage Under Average Recharge Conditions | Streamflow Under Drought Recharge Conditions; No Water Supply Withdrawals | Streamflow During Hypothetical Existing Average Annual Pumpage Under Drought Recharge Conditions | Streamflow During Hypothetical Existing Inseason Annual Pumpage Under Drought Recharge Conditions | Streamflow During Proposed 2020 Inseason Annual Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|---|
| Herring River | 10.30 | 9.88 | 9.62 | 9.24 | 8.32 | 7.88 | 7.61 | 7.23 |
| Bound Brook | 2.22 | 2.12 | 2.06 | 1.97 | 1.72 | 1.62 | 1.56 | 1.47 |
| Herring Brook | 3.56 | 3.42 | 3.33 | 3.19 | 2.89 | 2.74 | 2.64 | 2.50 |
| Duck Harbor | 0.77 | 0.77 | 0.77 | 0.77 | 0.62 | 0.61 | 0.61 | 0.61 |
| Perch Pd Dr. | 3.75 | 3.57 | 3.46 | 3.31 | 3.09 | 2.91 | 2.80 | 2.65 |
| Mill Creek | 0.75 | 0.74 | 0.74 | 0.74 | 0.66 | 0.66 | 0.65 | 0.65 |
| Upper Pamet River | 1.83 | 1.71 | 1.64 | 1.53 | 1.30 | 1.18 | 1.11 | 1.00 |

* Seasonal Data Not Simulated

[1] Calculated streamflows are relative rather than absolute. Due to an artifact of the model associated with wastewater flows, streamflow under 2020 pumpage conditions may not in reality be greater than those under existing conditions as indicated. However the model does indicate that streamflows do not significantly change due to increases in pumping in 2020.

Figure 35

# WATER SURFACE ELEVATION
# SELECTED WELLFLEET FLOW CELL PONDS



6. Truro Flow Cell


| Table/Figure | Description | Page |
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| Table 24 | Calculated pond and ground water levels for existing and proposed pumping during average and drought recharge conditions | 89 |
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| Figure 42 | Sharp Model - Truro saltwater interface, 1975 pumpage with drought conditions, cross section A-A' | 94 |
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DEM Office of Water Resources

The Truro flow cell, which includes the northern two-thirds of Truro, has an overlying land surface which is approximately two and three-quarter miles wide at its widest point and six miles long. It is bordered on the east by the Atlantic Ocean and west by Cape Cod Bay. The southern most edge is the Pamet River, in Truro, and the northern edge of the cell is Pilgrim Lake/Salt Meadow in northern Truro. The Truro flow cell is the smallest of the five potable flow cells and water table elevations range from sea level at the coasts to approximately six feet above sea level near the center of the peninsula. The Truro flow cell provides the water supply for the town of Provincetown because of the poor quality of water in the Provincetown flow cell.

The Sharp model was used to simulate changes in ground water elevation and saltwater/fresh water interface elevation in the Truro flow Cell (Figure 36). The simulations include pumping scenarios for pre-development conditions and the years 1975, 1989, and 2020. Drought conditions were simulated for 1989 and 1975. In-season and off-season scenarios were simulated for 1989. Resulting ground water elevations at environmentally sensitive locations and well nodes are shown in Tables 23 and 24 for each

Figure 36

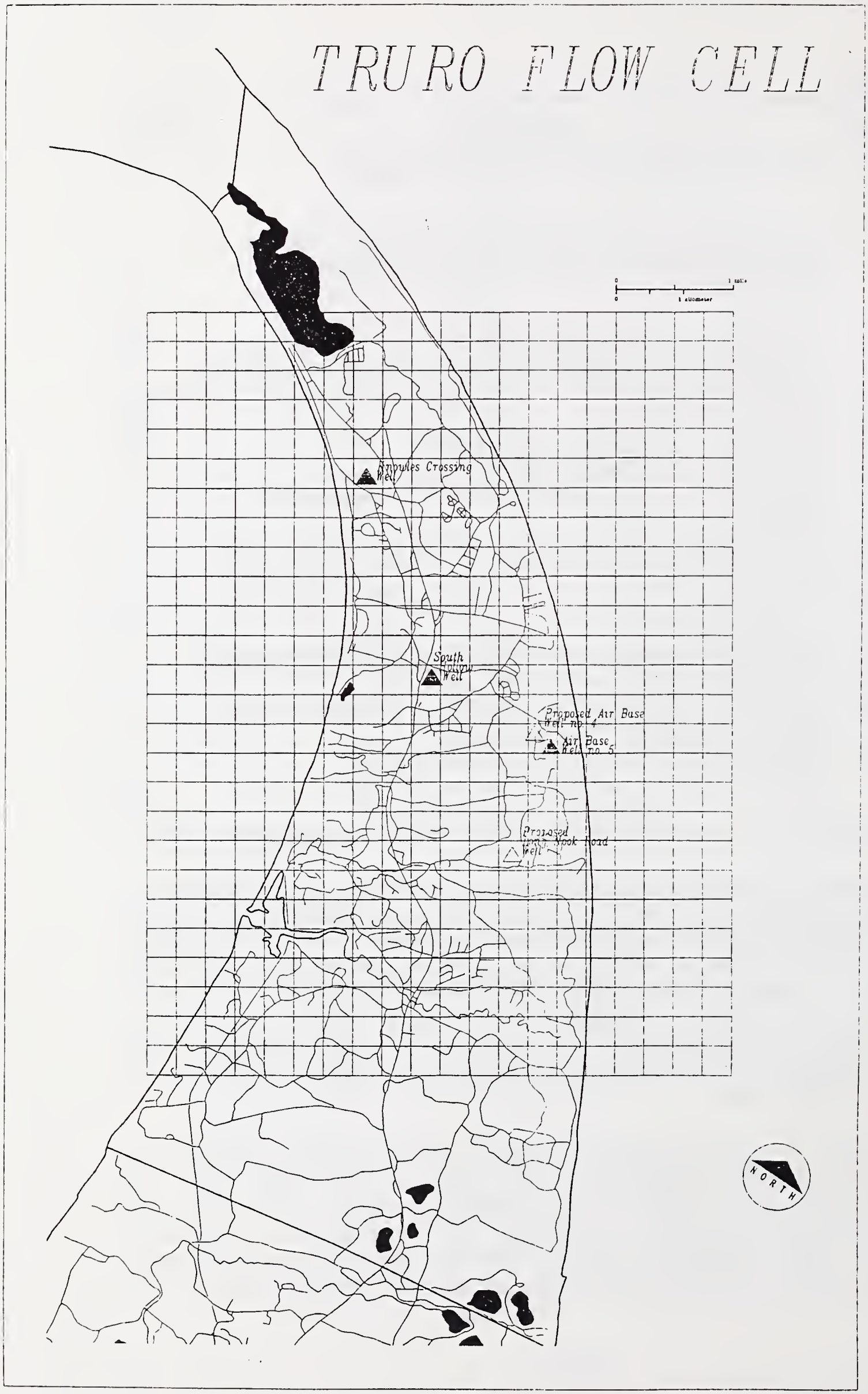

TRURO FLOW CELL
Knowles Crossing Well
South Hollow Well
Proposed Air Base Well no. 4
Air Base Well no. 5
Proposed Cook Road Well
NORTH

Figure 37 shows the Truro flow Cell with the existing and proposed wells and the environmentally sensitive nodes for which ground water elevations are reported. Also pictured are the cross section locations. Cross section A-A' runs north south along the eastern coastline of the Truro area through the existing and proposed Air Base wells. Cross sections B-B' and C-C' run west to east through the South Hollow well site and the Knowles Crossing well site, respectively. These cross sections were chosen based on nodes which showed changes in the salt water-fresh water interface. Table 23 shows total existing and projected pumpage in the Truro flow Cell for existing and proposed wells shown in Figure 38.

**Table 23**

**Truro Flow Cell Current and Projected Pumping**

| Community | Map Symbol | 1989 In-Season Pumpage | 1989 Off-Season Pumpage | Projected 2020 In-Season Pumpage | Projected 2020 Off-Season Pumpage | Pumping Capacity |
|---|---|---|---|---|---|---|
| Provincetown | A-E | 1.32 | 0.63 | 2.25 | 0.66 | 2.57 |

DEM Office of Water Resources

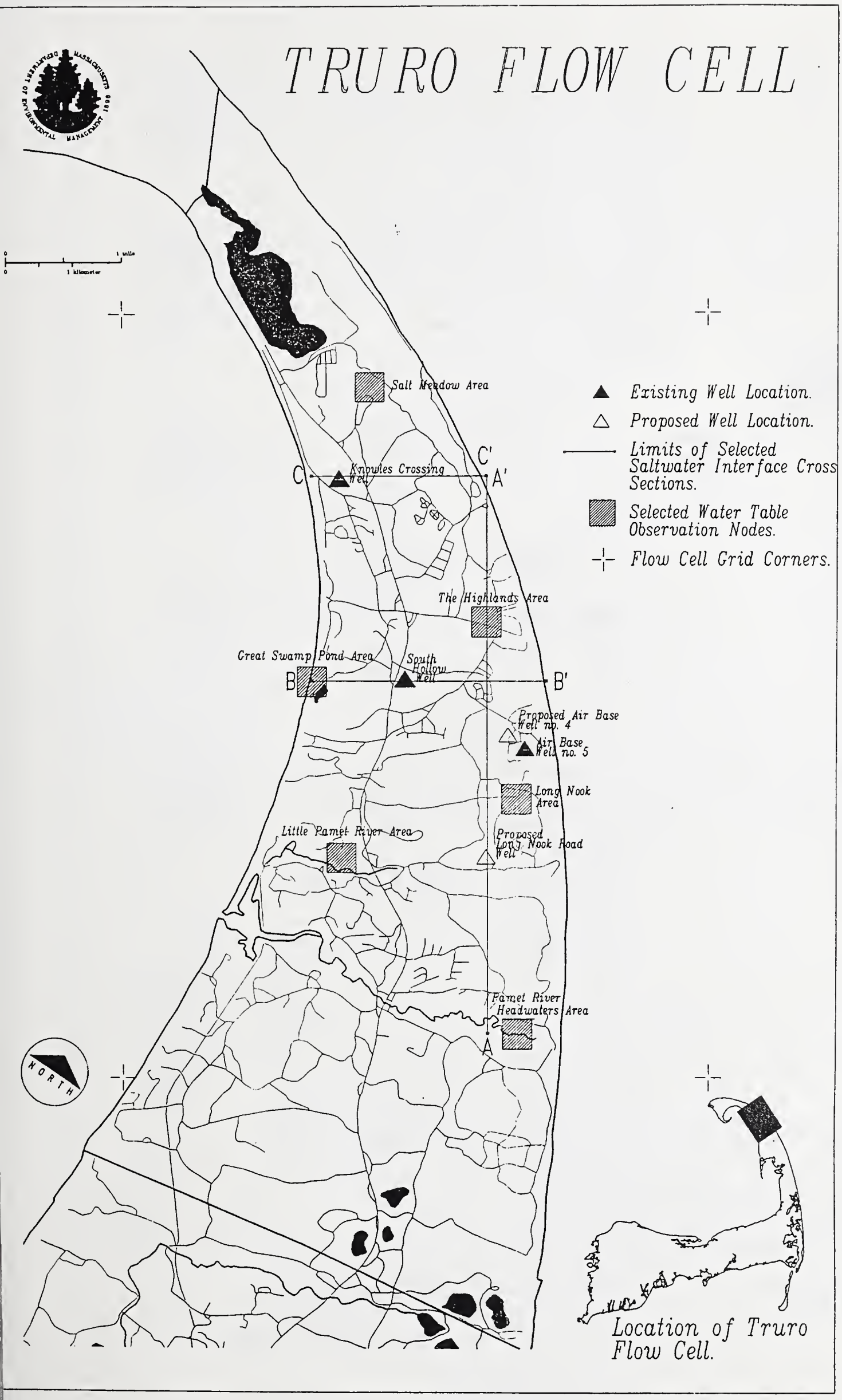
As shown in Figures 39 and 40 (sections A-A' and B-B') the fresh water-salt water interface is about 200 feet below the Air Base and South Hollow wells. Both sets of wells show some upconing due to pumpage from pre-development through 2020; however, maximum changes in the interface elevation are small relative to the depth of the interface. Figure 41 (section C-C') shows significant upconing of the interface below the Knowles Crossing well from pre-development through 2020. At this location the interface was only 80 feet below the elevation of the well during pre-development conditions. The interface was highest in 1975 when pumping was highest and some salt water intrusion occurred. For 1989 and 2020 pumpage was decreased from 1975 pumpage to reflect a reduced dependance on the Knowles Crossing well. The reduced pumpage resulted in higher ground water levels and a lower salt water interface, to avoid salt water contamination. The ground water elevations for pre-development, 1975, 1989 and 2020 are shown in Table 24. In general the elevation drops in response to increased pumping. Some elevations increased in 2020 due to decreased use of some wells as mentioned above.

Drought simulations for 1975 and 1989 pumpage result in decreases in the water table and increases in the interface elevation. Ground water elevations for drought conditions and 1975 and 1989 pumpage are shown in Table 24. The changes in the interface are shown for cross section A-A' (Figures 42 and 43). Drought conditions applied with 1975 pumpage raise the interface elevation 2.5 times the change caused by the 1975 pumpage alone. Drought conditions applied with 1989 pumpage change the interface elevation 1.5 times as much as the 1989 pumpage conditions alone.

In-season and off-season pumpage scenarios for 1989 are shown in Figure 44 (cross section B-B'). The figure shows a significant difference between the pre-development interface and

both the 1989 in-saeson and off-season interfaces, but very little difference between the in-season and off-season interfaces. The interface does not change much from the three month (higher) in-season pumpage to the nine month (lower) off-season pumpage. However, ground water elevations shown in Table 25 for pre-development, 1989 average and 1989 in-season and off-season pumpages do change from one season to the next. Water levels drop below the 1989 average level during in-season pumpage when demands are higher and are slightly higher than the 1989 average level during the off-season when demands are lower. The salt water interface does not react as quickly as the ground water table to the seasonal changes in demand and remains slightly higher than average.

Figure 37


TRURO FLOW CELL
Salt Meadow Area
Knowles Crossing Well
C
C'
A'
The Highlands Area
Great Swamp Pond Area
South Hollow Well
B
B'
Proposed Air Base Well no. 4
Air Base Well no. 5
Long Nook Area
Little Pamet River Area
Proposed Long Nook Road Well
Pamet River Headwaters Area
A
NORTH
Existing Well Location.
Proposed Well Location.
Limits of Selected Saltwater Interface Cross Sections.
Selected Water Table Observation Nodes.
Flow Cell Grid Corners.
Location of Truro Flow Cell.

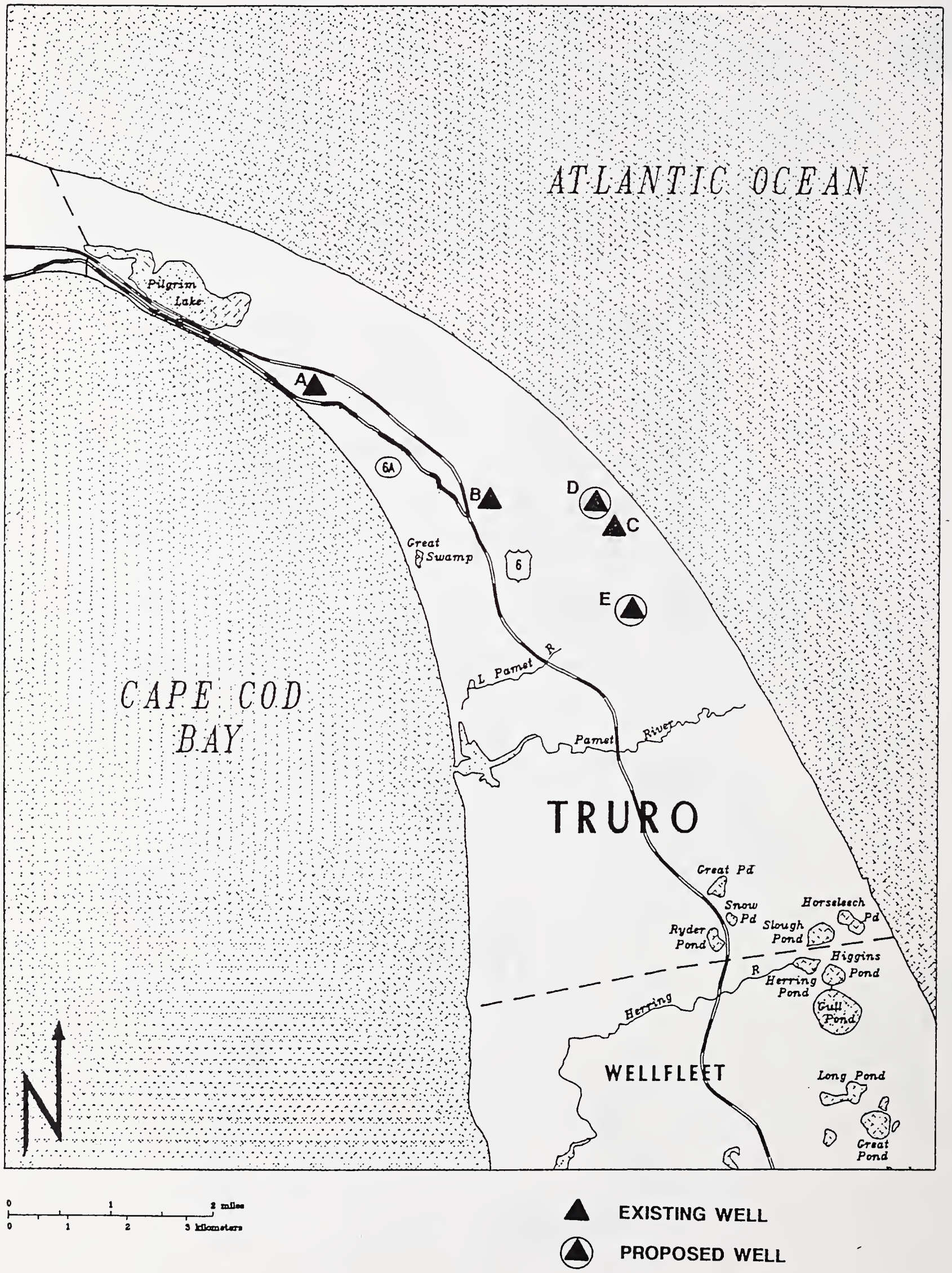

ATLANTIC OCEAN
Pilgrim Lake
A
6A
B
D
C
Great Swamp
6
E
L Pamet R
Pamet River
CAPE COD BAY
TRURO
Great Pd
Snow Pd
Horseleech Pd
Slough Pond
Ryder Pond
Higgins Pond
R
Herring Pond
Gull Pond
Herring
WELLFLEET
Long Pond
Great Pond
N
0 1 2 mile
0 1 2 3 kilometers
EXISTING WELL
PROPOSED WELL

Table 24

Calculated Pond and Ground Water Levels for Existing and Proposed Pumpage During Average and Drought Recharge Conditions, in feet above NGVD*
Truro Flow Cell

| Location | Node | Ground Water Levels Under Average Recharge Conditions; No Water Supply Withdrawals | Ground Water Levels During Hypothetical 1975 Average Annual Pumpage Under Average Recharge Conditions | Ground Water Levels During Hypothetical 1989 Average Annual Pumpage Under Average Recharge Conditions | Ground Water Levels During Proposed 2020 Annual Pumpage Under Average Recharge Conditions | Ground Water Levels During Hypothetical 1975 Average Annual Pumpage Under Drought Recharge Conditions | Ground Water Levels During Hypothetical 1989 Average Annual Pumpage Under Drought Recharge Conditions |
|---|---|---|---|---|---|---|---|
| Great Swamp | 7 14 | 2.71 | 2.54 | 2.52 | 2.08 | 2.47 | 2.36 |
| Little Pamet River | 8 8 | 4.81 | 4.72 | 4.73 | 4.81 | 4.48 | 4.29 |
| Salt Meadow | 9 24 | 2.01 | 1.84 | 1.92 | 1.73 | 1.78 | 1.79 |
| The Highlands | 13 16 | 4.31 | 4.12 | 4.10 | 3.93 | 3.94 | 3.82 |
| Pamet River Headwaters | 14 2 | 3.57 | 3.55 | 3.56 | 3.50 | 3.43 | 3.41 |
| Longnook Area | 14 10 | 5.14 | 4.99 | 4.91 | 4.57 | 4.73 | 4.58 |
| Knowles Crossing Well | 8 21 | 3.30 | 1.70 | 2.82 | 3.16 | 1.78 | 2.64 |
| South Hollow Well | 10 14 | 5.41 | 3.96 | 3.68 | 4.52 | 3.81 | 3.31 |
| Air Base Wells | 14 12 | 4.87 | 4.72 | 4.37 | 3.92 | 4.49 | 4.05 |
| Proposed Longnook Well | 13 8 | 5.78 | 5.69 | 5.66 | 4.83 | 5.35 | 5.27 |

* National Geodetic Vertical Datum

Table 25

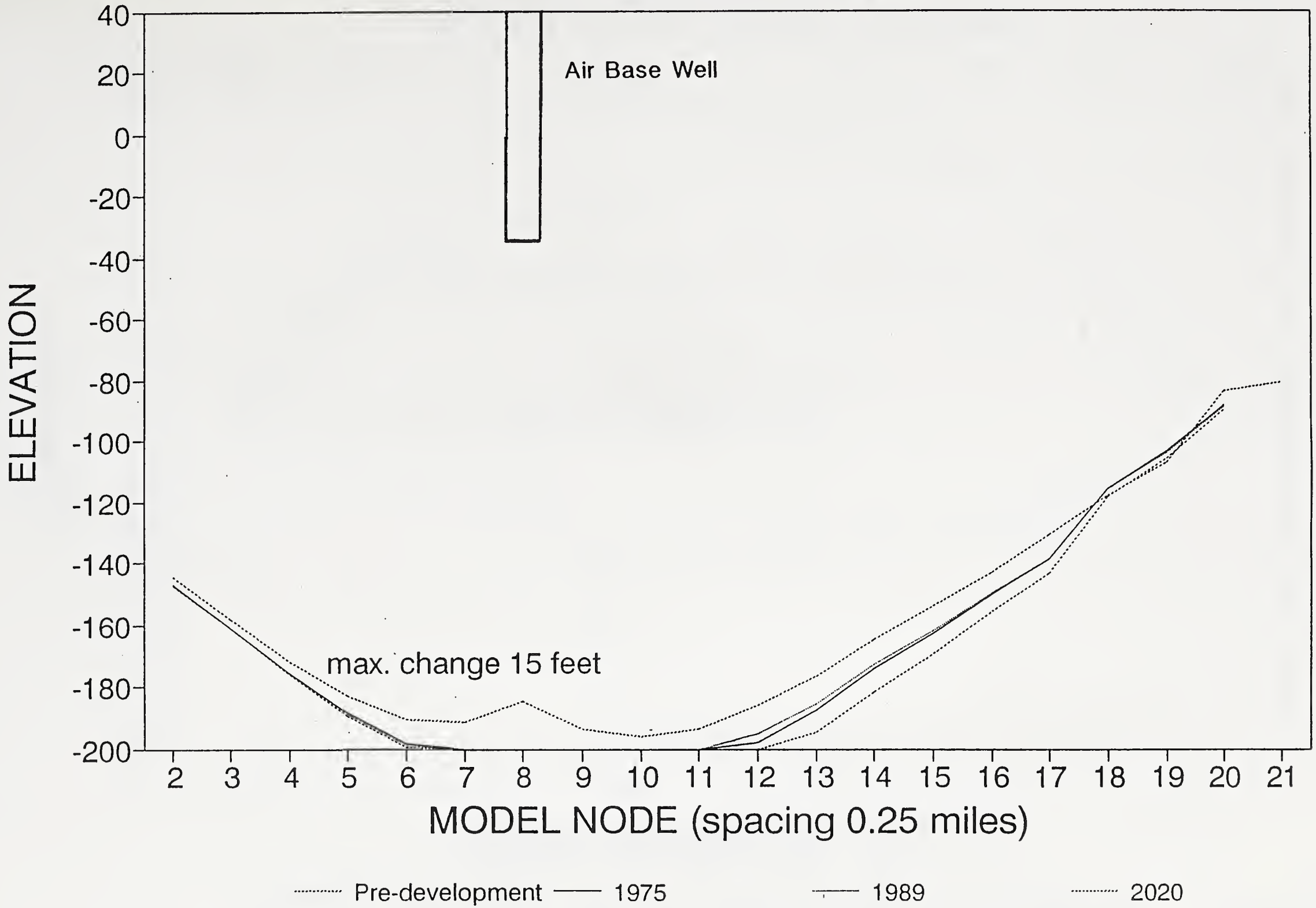
Calculated Pond and Ground Water Levels for Existing, In-Season and Off-Season Pumpage During Average Recharge Conditions, in feet above NGVD*
Truro Flow Cell

| Location | Node | Ground Water Levels Under Average Recharge Conditions; No Water Supply Withdrawals | Ground Water Levels During Hypothetical 1989 Average Annual Pumpage Under Average Recharge Conditions | Ground Water Levels During Hypothetical 1989 In-season Pumpage Under Average Recharge Conditions | Ground Water Levels During Hypothetical 1989 Off-season Pumpage Under Average Recharge Conditions |
|---|---|---|---|---|---|
| Great Swamp | 7 14 | 2.71 | 2.52 | 2.38 | 2.58 |
| Little Pamet River | 8 8 | 4.81 | 4.73 | 4.60 | 4.83 |
| Salt Meadow | 9 24 | 2.01 | 1.92 | 1.81 | 2.03 |
| The Highlands | 13 16 | 4.31 | 4.10 | 3.94 | 4.18 |
| Pamet River Headwaters | 14 2 | 3.57 | 3.56 | 3.50 | 3.52 |
| Longnook Area | 14 10 | 5.14 | 4.91 | 4.78 | 5.01 |
| Knowles Crossing Well | 8 21 | 3.30 | 2.82 | 2.65 | 3.21 |
| South Hollow Well | 10 14 | 5.41 | 3.68 | 3.06 | 3.70 |
| Air Base Wells | 14 12 | 4.87 | 4.37 | 4.08 | 4.51 |
| Proposed Longnook Well | 13 8 | 5.78 | 5.66 | 5.54 | 5.76 |

* National Geodetic Vertical Datum

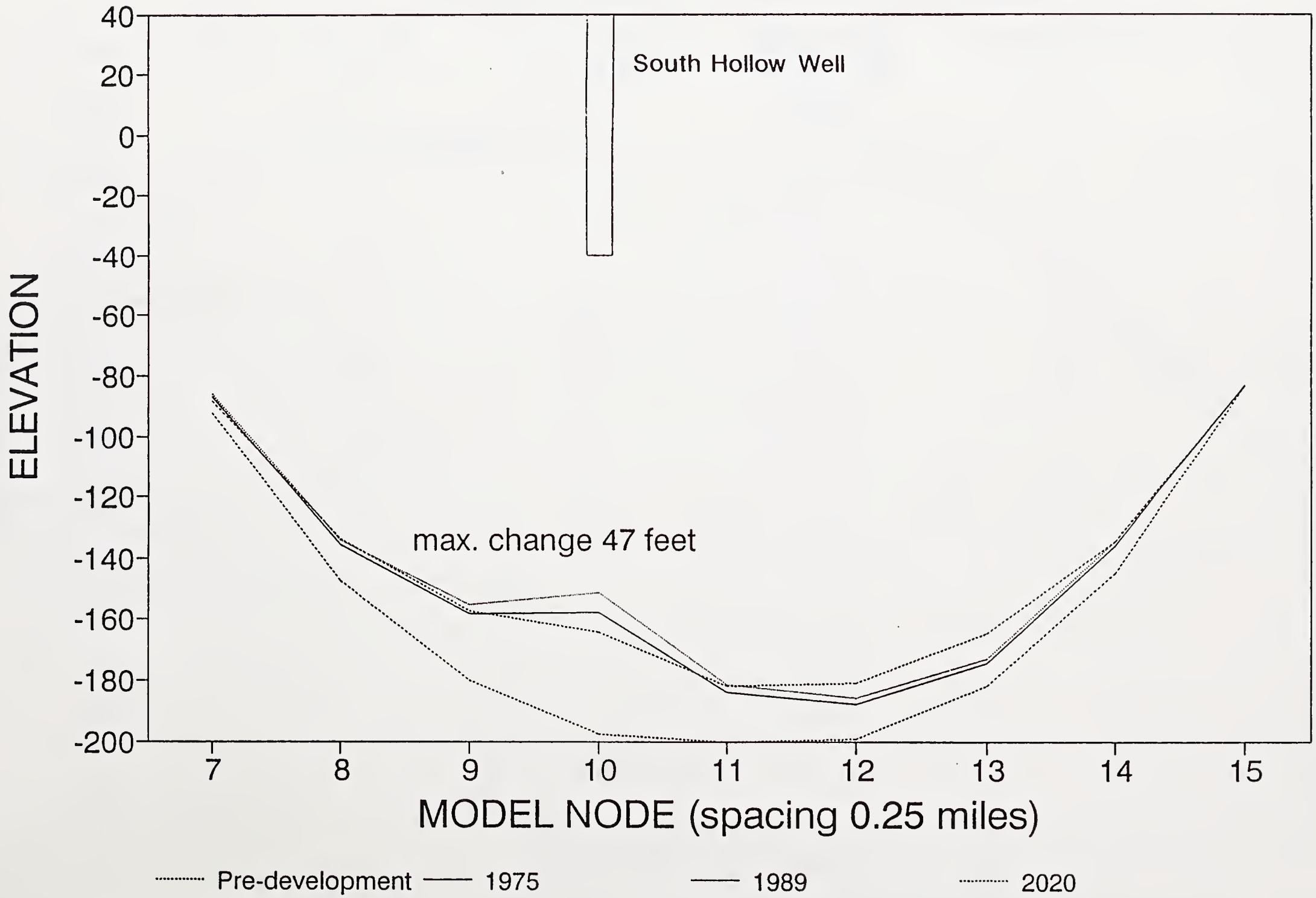
# Sharp Model - Truro Saltwater Interface
# Cross Section A - A'

Figure 39



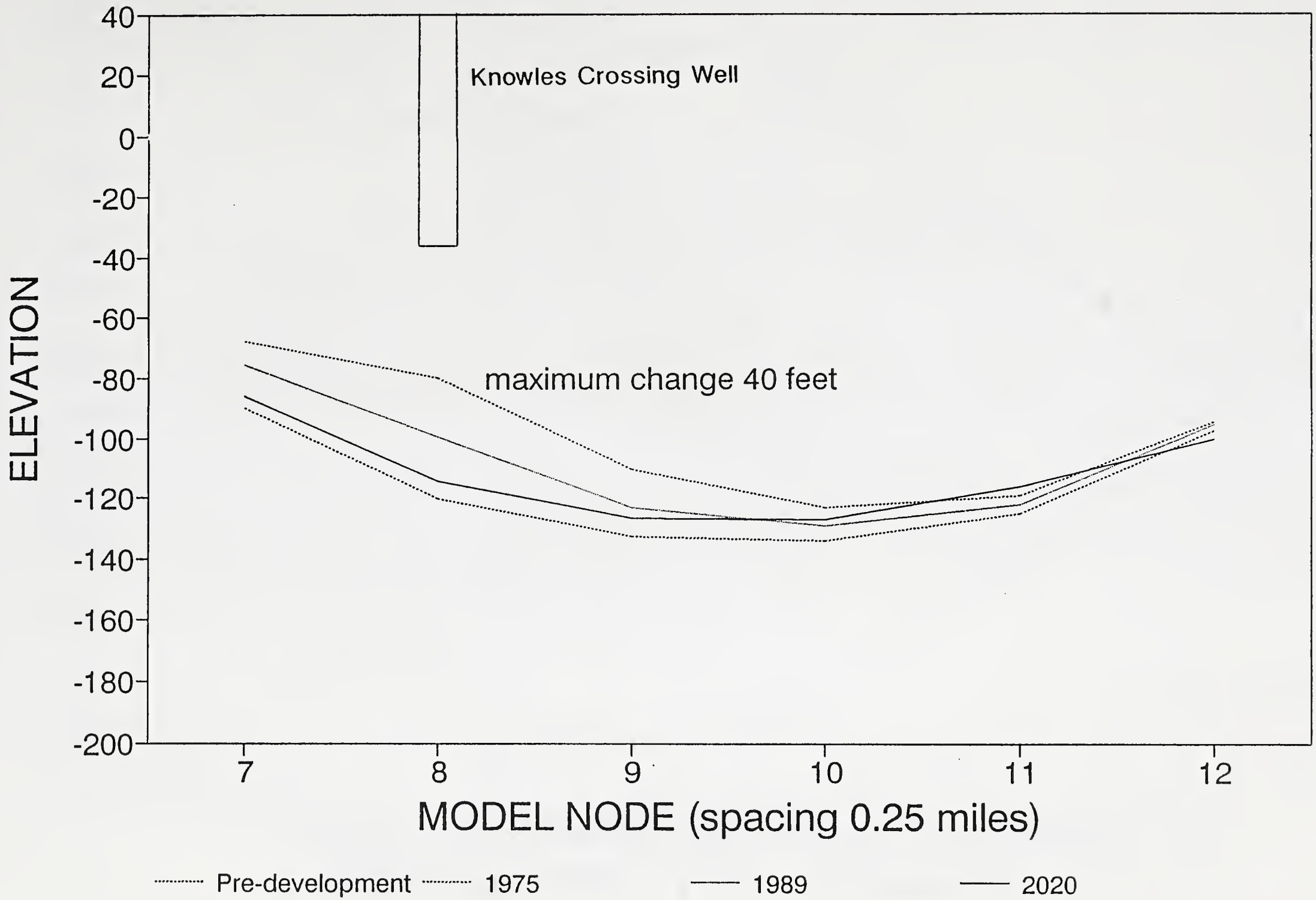
# Sharp Model - Truro Saltwater Interface
# Cross Section B - B'

Figure 40



# Sharp Model - Truro Saltwater Interface
# Cross Section C - C'

Figure 41



# Sharp Model - Truro Saltwater Interface
# 1975 Demands, Drought Conditions, A-A'

Figure 42

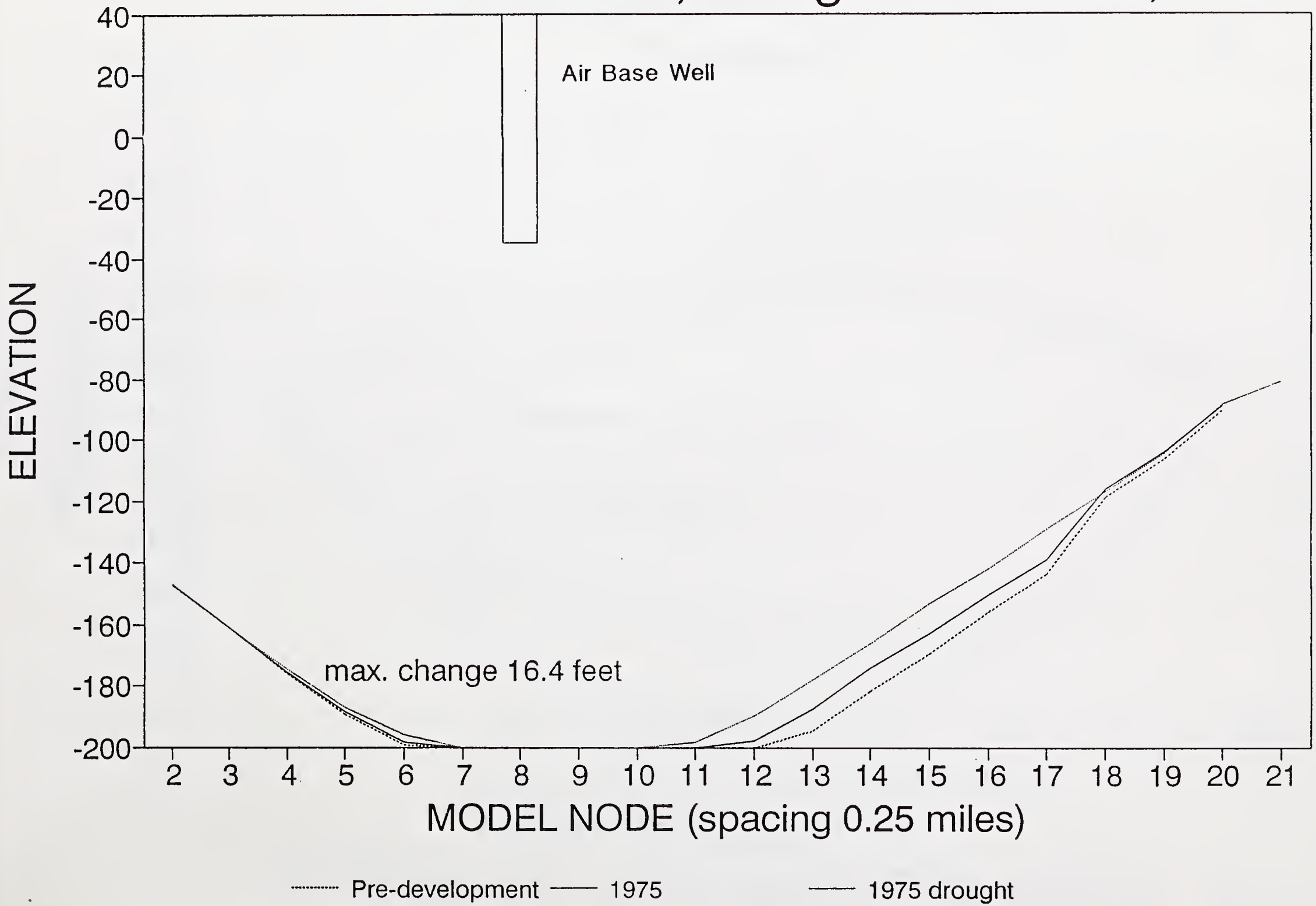
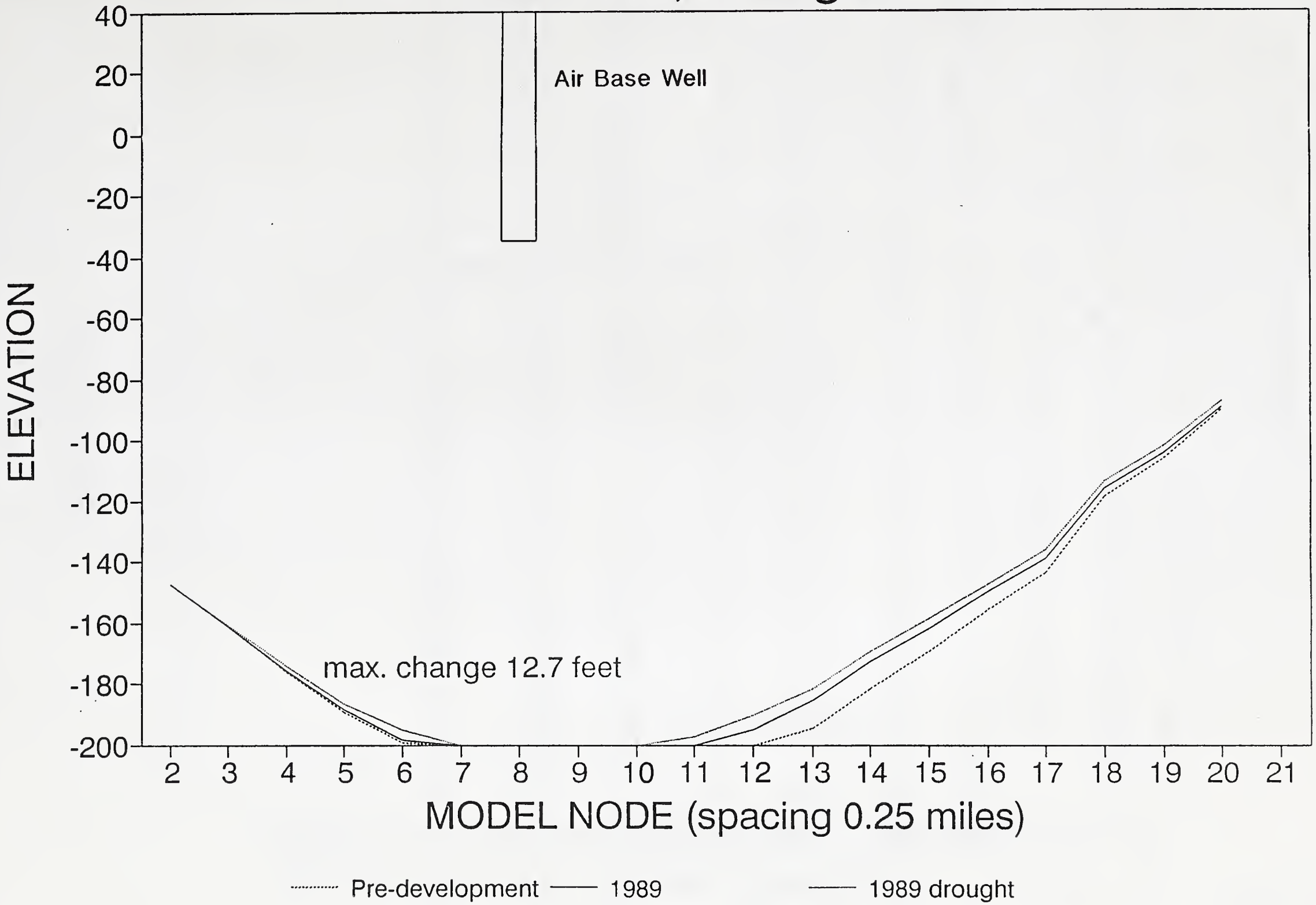


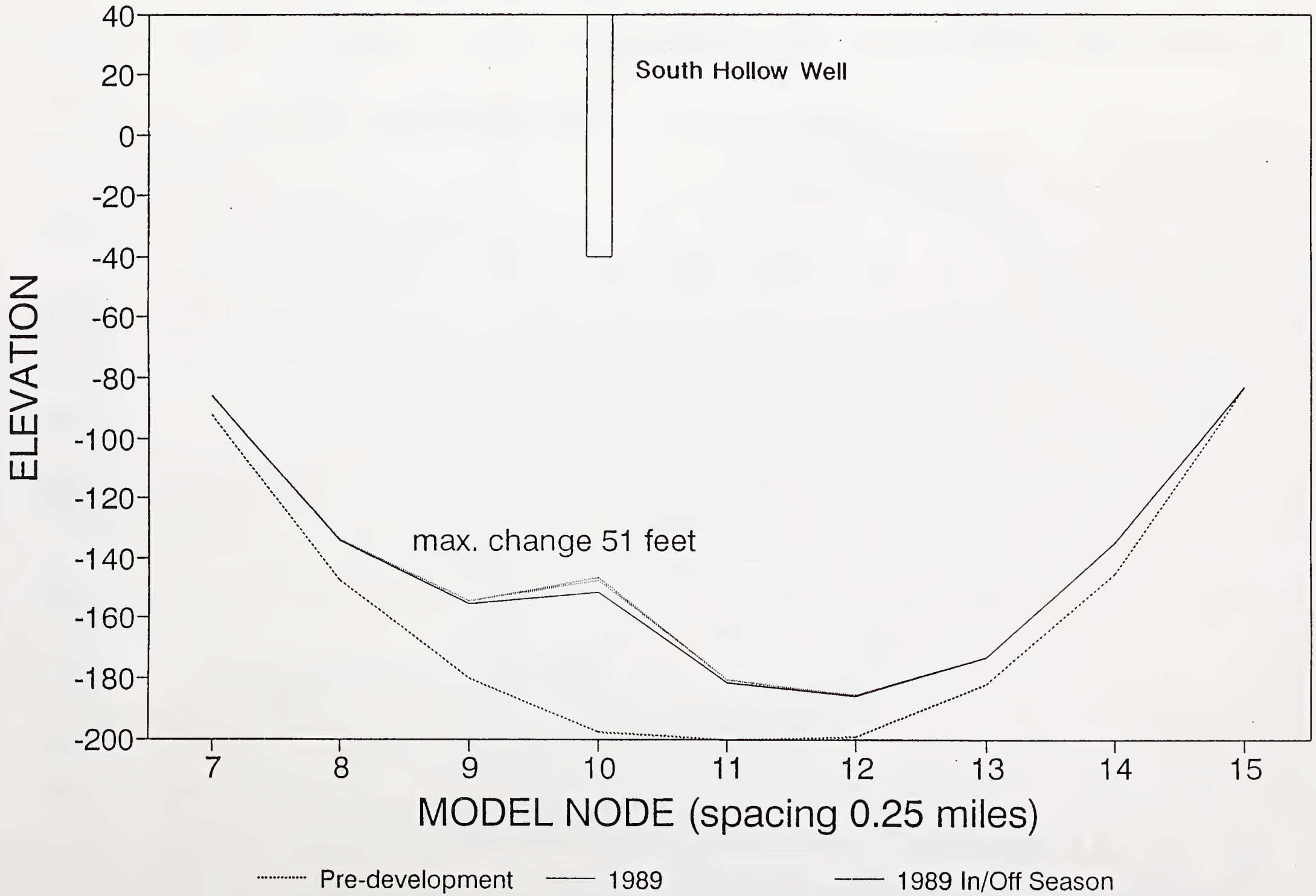
Figure 43

# Sharp Model - Truro Saltwater Interface
# 1989 Demands, Drought Conditions,A - A'



# Sharp Model - Truro Saltwater Interface
# 1989 Inseason/Offseason, Section B - B'

Figure 44



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APPENDIX A

**Massachusetts Water Resources Commission**

**River Basin Planning Program**
**Generalized Water Needs Forecasting Methodology**

Municipal Water Needs Forecast

The methodology for forecasting public water supply needs for each basin uses a disaggregated approach, based on the most recent five year's water use (called Base Demand) for each community in the study area. The three main water use categories for each community are residential, non-residential (including commercial, industrial, agricultural, municipal), and unaccounted-for water (UAW).

The main assumptions of the disaggregated approach and the calculations used to arrive at the disaggregated 2020 forecast shown are detailed below.

"Method 1", shown in Table 1, is used to arrive at water use forecasts for those communities which

- are able to provide sufficient disaggregated water use data
- show a residential gallons per capita daily use (gpcd) of 80 or less
- have an unaccounted-for water factor of 15% or less

For communities that have insufficient data to develop a disaggregated water use forecast, have a residential gpcd over 80, or a high percentage of unaccounted-for water, Method #2, shown in Table 2, has been used.

**Disaggregated Water Needs Forecast - Method #1**

1. Columns B through H show 1990 census estimate and Base municipal water demand data (base demand). Column E, 1990 seasonal population factor was calculated by multiplying the summer population by 3 (for the 3 summer months), dividing this number by 12 (for the year). Column F, the 1990 base service population, is calculated by multiplying Column B, the 1990 federal census estimate by Column C, the percent of the population served by the water supplier, then adding Column D, the out of town population and Column E, the seasonal population factor, to this product. The water demand information was obtained from the water supplier for each community and from Department of Environmental Protection (DEP).

2. Columns I through K show the residential portion of the base average day demand (ADD). The percentage of residential water use is shown in column I. The residential gpcd, shown in column J, is calculated by dividing K by F.

3. Columns L and M, non-residential water use, are based on information provided by the community or DEP.

4. Columns N and O, unaccounted-for water (UAW), are obtained by subtracting the residential and non-residential water use from the total water use in G; thus O=(G-[K+M]). UAW consists of domestic and non-domestic meter underregistration, potentially recoverable and unavoidable leakage, and unmetered use, especially public unmetered use. The data were obtained either from DEP statistical sheets or from personal interviews with the water supplier for each community.

5. Columns P through S show how residential water use is projected to change through 2020. The 2020 service population, column R, is calculated from the 2020 population projection, column P, and the estimated percentage of the population served in 2020. The 2020 service population is multiplied by the existing residential gpcd, column J, to obtain the 2020 residential water use shown in column S. All the communities in Table 1 have existing residential gpcd at or below 80, so their existing gpcd is carried forward.

6. Column T, the 2020 non-residential portion of projected demand, is calculated by adding two factors to existing non-residential water use:

(a) <u>Additional non-residential ADD due to population change</u>

Projected population change between 1990 and 2020 is multiplied by the existing "non-residential gpcd" (column L times column H) which results in the new non-residential ADD for the additional population. (In cases where population is projected to decline, this non-residential water use also will decline.)

$$[(L \times H) \times (R - F)]$$

(b) <u>Allowance for new non-residential uses independent of population change</u>

Communities often experience changes in commercial or industrial sectors which is not directly linked to population change. In order to plan for changes in non-residential water use not tied to population change, and in lieu of specific economic projections for each community, a growth factor based on past economic trends is included in the equation for column T.

The average non-residential water use was estimated over the past 10 year period. The volume change between the first three years of the period and the last three years was used to estimate the change expected to occur in succeeding decades, unless the community could provide specific information. Where non-residential water use has shown a decline between the two periods, the non-residential water use is held constant.

7. In calculating Column U, unaccounted-for water, the methodology assumes that if existing UAW is 10 percent or lower, the existing percentage will continue in the future.

If the UAW is greater than 10%, it is assumed that there will be a reduction in UAW during the planning period to reach 10%.

8. Column V, the 2020 ADD, was calculated by adding columns S, T, and U.

**Water Needs Forecast - Method #2**

Method #1 could be applied in those communities where it was possible to obtain disaggregated data on residential, non-residential, and UAW in order to project those components. Due to a low percentage of metering and/or inaccurate metering, a number of communities do not have adequate data to permit a disaggregated water use forecast.

The method assumes that the gpcd of any additional population will have a gpcd of no more than 70, and makes no allowance for unaccounted-for water. Therefore, towns which have a high residential gpcd (greater than 80) and/or a high unaccounted-for water component (greater than 15%) are subject to Method 2.

The main assumptions of Method #2 and the calculations used to arrive at 2020 demand projections shown in Table 2 are detailed below.

1. Columns B through H are calculated as in Method #1.

2. Columns I through O are shown where possible, or otherwise shown as unknowns. Until these communities are either more fully metered or are able to reliably distinguish their UAW, a disaggregated methodology cannot be used.

3. Columns P through R are the same as in Method #1 and show the change in service population through 2020.

4. Column S shows the increase in the residential service population between 1990 and 2020, and is derived by subtracting F from R.

5. Column T is the residential gpcd factor of 70 assumed for all new population growth. Because of wider enforcement of the plumbing code and the increased use of residential water conservation devices, it is expected that there will be a reduction in residential gpcd over the planning period.

6. Column U shows the additional increase in residential demand between 1990 and 2020, based solely on population change, and is derived by multiplying S by T.

7. One part of Column V, the 2020 non-residential portion of projected demand, is calculated as shown in Step 6(a) of Method #1. For the portion of growth in non-residential sectors independent of population change, a method similar to step 6(b) was used with a slight variation. As in Method 1, the average non-residential water use was estimated for the first and last three years of the previous decade. The volume change in non-residential water use for this time period was then determined. However, for Method #2

communities, the growth rate was slowed to reflect the inadequacy of the information and the assumption that additional water is available in the water supply system.

8. The 2020 ADD, column X, was calculated by adding the base ADD, column W, to the increase in residential demand, column U, and column V, the increase in non-residential demand.

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Natural Heritage & Endangered Species Program

Commonwealth of Massachusetts
Division of Fisheries & Wildlife
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# Natural Community Fact Sheet: Coastal Plain Pond Shores

## Description

Coastal Plain Pond Shore communities are composed of a mixture of herbaceous and graminoid species growing on the exposed margins of coastal plain ponds, between the shallow water and the shrubs that surround freshwater ponds in sandy deposits of Massachusetts coastal areas. Bare patches of sand, sandy to muddy peat, or cobbles occur between the plants.

## Environment

Coastal plain ponds occupy depressions in glacial outwash plains that are directly linked to the underground aquifer. The Coastal Plain Pond Shore community occurs in those ponds with no surface inlet or outlet, and with a gradual slope to the shore. The community develops best in small ponds or bays of larger ponds with little space for wind sweep that causes wave and ice damage to shorelines on large ponds. In most cases the substrates are sand or sandy glacial till through which the water moves easily. As a result, the water level rises and falls with the water table through the seasons, which in most years leaves exposed shores expanding throughout the summer. Many of the plant species of the community are able to start growth from seed, perennial basal leaves, or roots while inundated with water in the spring and grow in the increasingly dry, nutrient poor soils as the season progresses; others may germinate only when exposed. In wet years the water level does not recede as far as in dry years, and the constituent species may grow vegetatively while submerged, with little flowering, or may not grow or germinate at all. Not only do the water levels change through the year, but between years as well: only one year in about 5 may be dry enough for the community to develop fully. The lowering of water levels during the growing season is probably the single most important factor in providing suitable habitat for the plants of the pond shore community.

The waters of coastal plain ponds tend to be nutrient poor and acidic, as is typical of eastern Massachusetts. The plants of the pond shore community are particularly adapted to the nutrient poor conditions, and although often restricted to that environment, are able to compete with more widespread plants that require more nutrients. The periodic inundations of the shore also help to keep out shrubs and upland plants, and the periodic drying keeps out the obligate aquatic plants.

Schematic representation of Coastal Plain Pond Shore community zonation

The figure shows a highly diagrammatic pond shore in a summer with low water. On the left is a highbush blueberry growing where it is seldom inundated. Down slope are a grass, New England Boneset, Threadleaved Sundew, Plymouth Gentian, and rushes. The Slender Arrowhead, Bayonet Rush, and aquatic plants are in the water. 1990

## Characteristic Species of Coastal Plain Pond Shores in Massachusetts

The Coastal Plain Pond Shore community harbors a reservoir of globally restricted plants. Many seldom occur elsewhere although some may be locally abundant, mixed in with more common marsh emergents such as rushes, sedges, Blue-joint (Calamagrostis canadensis), Boneset (Eupatorium perfoliatum), Purple Gerardia (Agalinis purpurea).

The plants of the community appear to form zones between the water and the shrubs around the pond. The driest zone, inundated only in the highest water, may have New England boneset (Eupatorium leucolepis var. novae-angliae) or Maryland meadow-beauty (Rhexia mariana) both considered rare in Massachusetts. Thread-leaved sundew (Drosera filiformis), common on these ponds, but uncommon elsewhere, and spatulate-leaved sundew (D. intermedia) are other plants of the higher shoreline.

An intermediate area of beach provides habitat for most of the species of the Coastal Plain Pond Shore community. The globally restricted, but locally abundant, Plymouth gentian (Sabatia kennedyana) grows from the shallow water across a broad expanse of sand. Mixed in may be the yellows of golden-pert (Gratiola aurea) and goldenrod (Solidago tenuifolia) and the pink of pink tickseed (Coreopsis rosea).

In the submerged or water-saturated areas may be slender arrowhead (Sagittaria teres) or a bladderwort (Utricularia fibrosa or U. biflora). Some ponds have many of these species, some have only one or a few. Many of the ponds have a large variety of rushes, sedges, and pipeworts that grow out into the open water.

## Range

Coastal Plain Pond Shore communities occur primarily on the Atlantic Coastal Plain, which extends from Texas and Florida to southern New Jersey, and in disjunct areas to Nova Scotia. Many of the species (Maryland Meadow Beauty, several bladderworts, and some of the sedges and rushes) are at the northern end of their distribution in southeastern Massachusetts. Cape Cod, southern Plymouth County, and Rhode Island have the best examples of Coastal Plain Pond Shore communities in New England. Southern ponds dry out in most years, and are called "bays". Those in glaciated regions have a much longer wet cycle, but their species composition is similar.

The New England pond shores occur in sandy substrate and kettle hole topography. There are several ponds on outwash sand plains in the Connecticut River Valley in south central Massachusetts that function similarly to coastal plain ponds, but which support fewer species. Nova Scotia has a few coastal plain ponds with some of the same species as the community found in Massachusetts, and interestingly, many occur in the Great Lakes region in southwestern Michigan and central Wisconsin.

## Status in Massachusetts

Coastal Plain Pond Shore communities have several immediate and long-term threats caused by human disturbance. The community requires natural fluctuation of the water levels along the shore. Artificially maintained high water levels reduce the area of shore available for the pond shore community. Most of the plants of the community can withstand high water for a few years, which happens naturally, but most need to be out of water to reproduce. Human use of the pond shores, including walking, offroad vehicles, and beach building, restricts plant growth. Experiments have shown that a few walking trips can create a trail where no plants grow. In areas of heavy use, the plants of the Coastal Plain Pond Shore community can easily be eliminated. High nutrient leachate from improperly maintained septic systems poses the long-term threat of pond eutrophication. Overwintering populations of Canada geese may provide sufficient nutrient enrichment to change the character of the ponds, allowing algae and pondweeds not native to the ponds to grow and reduce the habitat available to the plants of the pond shore community. Excessive drawdown from pumping for water consumption reduces natural fluctuations and allows woody species to advance down the shores.

## Coastal Plain Pond Sites in Barnstable County

| Key | SITENAME | BIODIVSIG | LOCALJURIS: |
|---|---|---|---|
| S.USMAFO*113 | GRASSY POND DENNIS | B3 | DENNIS |
| S.USMAFO*115 | SIMMONS PONDS | B3 | DENNIS |
| S.USMAFO*116 | CROOKED POND COMPLEX FALMOUTH | B2 | FALMOUTH |
| S.USMAFO*119 | HAWKSNEST POND COMPLEX | B3 | HARWICH |
| S.USMAFO*29 | BAKER POND ORLEANS | B3 | ORLEANS |
| | | | BREWSTER |
| S.USMAFO*36 | MARY DUNN POND COMPLEX | B2 | BARNSTABLE |
| S.USMAFO*64 | SOLS/BLUEBERRY PONDS | B3 | BREWSTER |
| S.USMAFO*70 | WEEKS POND | B3 | SANDWICH |
| S.USMAFO*72 | ELBOW POND COMPLEX | B3 | BREWSTER |
| S.USMAFO*79 | AUNT PATTYS POND | B2 | DENNIS |
| S.USMAFO*86 | OWL/LEES PONDS | B3 | BREWSTER |
| S.USMAHP*1041 | MARES POND/SPECTACLE POND FALMOUTH | B3 | FALMOUTH |
| S.USMAHP*1042 | GRASS POND HARWICH | B3 | HARWICH |
| S.USMAHP*1043 | BLACK POND HARWICH | B3 | HARWICH |
| | | | BREWSTER |
| S.USMAHP*1044 | SHEEP POND BREWSTER | B3 | BREWSTER |
| S.USMAHP*1045 | PONDVIEW ROAD BREWSTER | B3 | BREWSTER |
| S.USMAHP*1046 | LAWRENCE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1047 | TRIANGLE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1048 | SPECTACLE POND SANDWICH | B3 | SANDWICH |
| S.USMAHP*1049 | SHUBAEL POND | B3 | SANDWICH |
| S.USMAHP*1071 | SNAKE POND | | SANDWICH |
| S.USMAHP*123 | HATHAWAY PONDS | B3 | BARNSTABLE |
| S.USMAHP*163 | DENNIS POND COMPLEX YARMOUTH | B3 | YARMOUTH |
| S.USMAHP*189 | HOG PONDS | B2 | SANDWICH |
| S.USMAHP*34 | SHALLOW POND | B3 | BARNSTABLE |
| S.USMAHP*346 | MUD POND HARWICH/BREWSTER | B3 | HARWICH |
| | | | BREWSTER |
| S.USMAHP*356 | RUN POND | B2 | DENNIS |
| S.USMAHP*359 | HORSE POND COMPLEX | B2 | YARMOUTH |
| S.USMAHP*376 | MINISTER POND | B3 | EASTHAM |
| S.USMAHP*4 | PROVINCETOWN PONDS | B3 | PROVINCETOWN |
| S.USMAHP*410 | TRAILER PARK POND MASHPEE | B4 | MASHPEE |
| S.USMAHP*455 | SCHOOLHOUSE PONDS | B3 | CHATHAM |
| S.USMAHP*490 | LITTLE POND | B3 | BARNSTABLE |
| S.USMAHP*528 | HOXIE POND | B4 | SANDWICH |
| S.USMAHP*543 | MYSTIC LAKE/MIDDLE POND | B4 | BARNSTABLE |
| S.USMAHP*549 | BAKERS POND DENNIS | B4 | DENNIS |
| S.USMAHP*570 | PICTURE LAKE (FLAX POND) | B3 | BOURNE |
| S.USMAHP*581 | GRASSY POND FALMOUTH | B4 | FALMOUTH |
| S.USMAHP*642 | ISLAND POND HARWICH | B3 | HARWICH |
| S.USMAHP*649 | MUDDY POND BARNSTABLE | B3 | BARNSTABLE |
| S.USMAHP*652 | ROBBINS POND | B3 | HARWICH |
| S.USMAHP*67 | GRIFFITHS POND | B4 | BREWSTER |
| S.USMAHP*836 | MILL POND HARWICH | B3 | HARWICH |
| S.USMAHP*84 | BLACK POND/WHITE POND COMPLEX | B3 | CHATHAM |
| S.USMAHP*840 | PERCH POND | B3 | WELLFLEET |
| S.USMAHP*845 | ELISHAS POND | B4 | YARMOUTH |
| S.USMAHP*853 | WASHBURN POND | B3 | MASHPEE |
| S.USMAHP*854 | HAMBLIN POND | B3 | BARNSTABLE |
| S.USMAHP*856 | CEDAR POND | B3 | DENNIS |
| S.USMAHP*862 | UNCLE ISRAELS POND | B3 | ORLEANS |
| S.USMAHP*863 | GOULD POND | B3 | ORLEANS |
| S.USMAHP*936 | CLIFF POND COMPLEX | B2 | BREWSTER |
| S.USMAHP*944 | GREAT POND WELLFLEET COMPLEX | B4 | WELLFLEET |
| S.USMAHP*945 | KINNACUM POND COMPLEX | B3 | WELLFLEET |
| S.USMAHP*949 | GULL POND COMPLEX | B3 | WELLFLEET |
| | | | TRURO |
| S.USMAHP*960 | GOOSE POND | B3 | CHATHAM |
| S.USMAHP*962 | KEELER POND | B4 | BREWSTER |
| S.USMAHP*963 | BUCKS POND COMPLEX | B3 | HARWICH |

Source: Natural Heritage and Endangered Species Program
Massachusetts Division of Fisheries and Wildlife
Data current as of 3 January 1994

Biodiversity Ranks: B1 = Outstanding, B2 = Very High, B3 = High, B4 = Moderate

Appendix C

# ANALYSIS OF THE EFFECTS OF CHANGING PUMPAGE AND RECHARGE ON GROUND-WATER FLOW IN THE CAPE COD, MARTHA'S VINEYARD, AND NANTUCKET ISLAND BASINS, MASSACHUSETTS

By John P. Masterson and Paul M. Barlow

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## Approach

The approach for determining the effect of ground-water withdrawals to each of the three ground-water basins was guided by the availability of hydrogeologic data and previously developed ground-water-flow models for each basin, and the level of current, and anticipated future ground-water use in each basin. Because (1) there were more hydrogeologic data available for the Cape Cod flow system than there were for either the Martha's Vineyard or Nantucket Island basins, (2) ground-water-flow models existed for five of the six flow systems of Cape Cod (Guswa and LeBlanc, 1985 and P.M., Barlow, U.S. Geological Survey, written commun., 1992), and (3) the yearly withdrawal of ground water on Cape Cod is much greater than that of Martha's Vineyard and Nantucket, there was greater need for assessing the effects of changing stress conditions within the Cape Cod flow system than there is for either the Martha's Vineyard or Nantucket Island flow systems. Consequently, the effects of changing stress conditions within the Cape Cod flow systems were assessed by use of three-dimensional, transient, ground-water-flow models, whereas those effects on the Martha's Vineyard and Nantucket Island flow systems were assessed by means of a change-model method in which drawdowns resulting from inseason (summer months of June, July, and August) pumping stresses that were anticipated for 2020 were determined.

Of the five flow systems of Cape Cod, the West Cape and East Cape cells have had the largest amount of domestic, industrial, and agricultural development within them, and, consequently, the largest amount of ground-water use. Two flow models were developed for each of these two flow cells to assess the effects of changing stress conditions in each flow cell. The first flow model developed for each flow cell was a transient, three-dimensional, finite-difference computer code that simulates freshwater and saltwater flow separated by a sharp interface (referred to in the remainder of the report as the SHARP code, or the resulting SHARP models), developed by Essaid (1990). These SHARP models were used to assess the response of the boundary between the freshwater and saltwater flow systems to changing stress conditions.

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The previous models developed by Guswa and LeBlanc (1985) using the Trescott (1975) code were not used in this investigation for several reasons. First, they are not transient models and therefore could not allow a transient analysis of changing stress conditions in the flow cells. Second, the models of Guswa and LeBlanc (1985) do not simulate saltwater flow in the aquifers, which the SHARP code does. The models of Guswa and LeBlanc (1985) make use of the Ghyben-Herzberg approximation to the location of the freshwater-saltwater interface, which assumes that the saltwater zone adjusts rapidly to applied ground-water stresses (Essaid, 1990, p. 10). This assumption is not reasonable for the analysis of the short-term response of a coastal aquifer to changes in ground-water stresses. For this type of analysis it was necessary to include the influence of the saltwater flow system (Essaid, 1990, p. 10). Finally, the Ghyben-Herzberg approximation used in the models of Guswa and LeBlanc (1985) precludes the simulation of freshwater leakage into overlying zones of the aquifer that are saturated with saltwater, such as occurs in the Cape Cod basin, for example near Cape Cod Bay (LeBlanc and others, 1986, plate 2). The SHARP model, however, is capable of simulating this freshwater-saltwater dynamic.

The SHARP models also provided an estimate of the location of the interface between freshwater and saltwater, and of the discharge of freshwater to zones of overlying aquifer containing saltwater in each flow cell. These estimates were used only to specify the boundary conditions for models developed for each flow cell that simulated the flow of freshwater only. The transient, three-dimensional finite-difference ground-water-flow model developed by McDonald and Harbaugh (1988)--referred to in the remainder of the report as the MODFLOW code, or resulting MODFLOW models--was developed for the West Cape and East Cape flow cells. Freshwater flow models were developed for each of the two flow cells because (1) the SHARP freshwater-saltwater flow models indicated little movement of the freshwater-saltwater interface in these two flow systems for the stress conditions simulated and (2) they require less computational effort than the SHARP models and therefore may be more easily applied to the analysis of ground-water withdrawals

within the flow cells. However, the reader is urged to review the section of this report titled "Limitations of the Flow Models" prior to using the MODFLOW models for the analysis of stress conditions that are not similar to those reported here.

The Truro flow cell is the smallest of the five flow cells of the Cape that are used for water supply, and is the only source of water for the communities of Truro and Provincetown. Although the sand and gravel aquifer extends to bedrock, the freshwater flow system is bounded at depth by the transition zone between freshwater and underlying saltwater (Guswa and LeBlanc, 1985, LeBlanc and others, 1986). Upconing of the freshwater-saltwater interface and contamination by saltwater encroachment caused by ground-water withdrawals have been recorded at the Knowles Crossing wellfield, located 1,500 ft from the ocean (LeBlanc and others, 1986). Evidence of saltwater upconing and encroachment precludes the assumption of a static interface between freshwater and saltwater, and the use of MODFLOW for the analysis of changing stress conditions. Therefore, changing stress conditions in the flow cell were evaluated by means of the SHARP model.

The Eastham and Wellfleet flow cells currently (1992) do not have any large-capacity public-supply wells, and there is less data available on the hydrogeology of these flow cells than there is for the West Cape, East Cape, or Truro flow cells. Consequently, a simpler modeling approach was taken for analysis of the two flow cells. Freshwater models of each flow cell were developed using the MODFLOW code. These models simulate predevelopment flow conditions, which are assumed to exist at this time. These models were incapable of assessing the dynamics between the freshwater and saltwater flow systems, however, they were used to assess the effect of a six-month period of no recharge on ground-water and pond levels in the flow cells. Use of these models are urged to review the section "Limitations of numerical modeling analysis for Cape Cod basin" prior to applying the models to any assessment of the flow cells.

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Figures 4 and 5--near here

## Hydrologic System

The Cape Cod ground-water flow system is described in this report as six flow cells which are nearly independent under present hydrologic conditions (Guswa and LeBlanc, 1985). These flow cells are bounded laterally, in part by surficial surface water bodies, and by the saltwater flow systems of Cape Cod Bay, Nantucket Sound and the Atlantic Ocean. The interface between the freshwater and saltwater flow systems forms the lateral and lower boundaries of the freshwater system except where the freshwater lens is truncated by the underlying bedrock surface.

The ultimate source of freshwater for the Cape Cod Basin is from natural precipitation. Cape Cod receives an annual average of 45 in/yr of rainfall. Of this, 45 to 48 percent actually recharges the aquifer system (LeBlanc and others, 1986). The remaining rainfall is lost to evapotranspiration.

The water-table configuration for the Cape Cod Basin was characterized as six oblong mounds occupying the six flow cells. The highest water-table elevation corresponded to the highest land surface elevations as shown in figure 2. Ground-water flows radially out from these potentiometric highs toward streams between cells and the coastal discharge areas. Letty (1984) compiled hydrographs for 68 observation wells throughout Cape Cod for the period 1950-82. Annual fluctuations at individual sites ranged from 2 to 7 ft. Seasonal changes in aquifer recharge and ground-water use cause fluctuations in the water-table elevations. The highest annual water-table elevations occur during the early spring when recharge is the greatest and ground-water withdrawals are low. The lowest water-table elevations occur during the late summer when ground-water recharge is minimal, storage is depleted, and water use is highest. Water-table fluctuations vary in magnitude across the Cape and are dependent upon the proximity to the shoreline. Frimpter and Fisher (1983) have determined that water-table fluctuations are least near constant-head saline-surface water bodies. Exceptions are wells affected by tidally-controlled water bodies having large tidal ranges, such as the Cape Cod Canal.

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The vast majority of the lakes and streams of Cape Cod are hydraulically connected to the ground-water system, and therefore mirror the water-table response to changing stress conditions. However, within the moraine deposits, discontinuous lenses of fine material above the regional water-table result in perched water-table ponds such as Scargo Lake. These localized, perched water-tables are independent of fluctuations in the regional water-table and thus were not addressed in this study.

The fresh ground-water system is bounded laterally and at depth by the saltwater system. Freshwater is less dense than the surrounding saltwater forming lens-shaped bodies of freshwater underlain by saltwater. The zone of mixing between the freshwater and saltwater flow systems is generally much thinner than the total aquifer thickness and therefore this transition zone is considered negligible and the freshwater-saltwater interface is referred to as a sharp interface (Essaid, 1990). Under natural hydrologic conditions it is assumed that the freshwater and saltwater systems are in hydrodynamic equilibrium. Ground-water leaving the freshwater system as discharge to the shore is balanced by aquifer recharge from precipitation resulting in a static interface between the flow systems. Reduction in aquifer recharge and (or) increases in ground-water withdrawals may result in a reduction in the rate of coastal discharge causing the landward movement of the interface position, and possible saltwater contamination of public-supply wells.

## Aquifer Hydraulic Properties

Aquifer hydraulic properties of horizontal and vertical hydraulic conductivity, specific yield, specific storage, storage coefficient, and porosity are needed for an analysis of the response of the Cape Cod freshwater-saltwater flow system to changing stress conditions. These properties have been estimated for the flow system as part of this and previous investigations by analysis of aquifer tests, permeameter tests, and field tracer tests.

### Previous Investigations

Table 1 summarizes previous estimates of horizontal and vertical hydraulic conductivity from analysis of aquifer tests in the Cape Cod flow system. Other estimates of hydraulic conductivity of sediments of Cape Cod were not reported in table 2 because they did not include a description of the lithology of the aquifer at the test site. The estimates indicated that there was a general increase in horizontal hydraulic conductivity with increase in grain size, from about 40 ft/day for fine sand and silt to 300 ft/day for coarse to very coarse

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Table 1.--*Hydraulic conductivity of stratified drift of Cape Cod, Massachusetts, as determined in previous investigations by analysis of aquifer tests*

[$K_H$, horizontal hydraulic conductivity in foot per day; $Kv:K_H$, ratio of vertical to horizontal hydraulic conductivity; --, data not available]

| Predominant grain size | Well identifier | Latitude | Longitude | $K_H$ | $Kv:K_H$ | Source of data |
|---|---|---|---|---|---|---|
| Fine sand and silt | Mashpee 108 | 41 36 06 | 70 30 29 | 40 | 1:50 | Barlow and Hess, written commun. |
| Fine sand | Barnstable 406 | 41 39 13 | 70 22 15 | 160 | 1:30 | Barlow, written commun. |
| do. | Yarmouth 74 | 41 40 00 | 70 14 52 | 160 | 1:30 | do. |
| Fine to medium sand | Wellfleet 41 | 41 54 00 | 69 58 42 | 180 | 1:3-1:5 | do. |
| do. | Yarmouth 176 | 41 39 16 | 70 11 48 | 200 | -- | Guswa and LeBlanc, 1985 |
| do. | Falmouth 214 | 41 37 03 | 70 33 00 | 380 | 1:2-1:5 | LeBlanc and others, 1988 |
| Very fine to coarse sand | Truro 200 | 42 00 51 | 70 02 48 | 220 | 1:1-1:5 | Guswa and Londquist, 1976 |
| Fine to coarse sand | Mashpee 108 | 41 36 06 | 70 30 29 | 240 | 1:3 | Barlow and Hess, written commun. |
| do. | Yarmouth 59 | 41 40 10 | 70 13 53 | 220 | 1:10 | Barlow, written commun. |
| do. | Yarmouth 129 | 41 40 22 | 70 14 19 | 240 | 1:3-1:5 | do. |
| Coarse to very coarse sand | Orleans 37 | 41 45 16 | 69 59 39 | 300 | less than 1:10 | Guswa and LeBlanc, 1985 |

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Table 2.--*Horizontal hydraulic conductivity and specific yield of stratified drift of Cape Cod, Massachusetts, as determined by use of the Jacob-Cooper approximation method*

[T, transmissivity in foot squared per day; b, saturated thickness of aquifer in feet; K, horizontal hydraulic conductivity in foot per day; Sy, specific yield, dimensionless]

| Predominant grain size | Well identifier | Latitude | Longitude | T | b | K | Sy |
|---|---|---|---|---|---|---|---|
| Fine sand | Yarmouth 155 | 41 40 10 | 70 14 18 | 5000 | 40 | 125 | 0.15 |
| do. | Yarmouth 74 | 41 40 00 | 70 14 52 | 11000 | 60 | 180 | .02 |
| Fine to medium sand, gravel | Dennis 200 | 41 42 54 | 70 10 03 | 13000 | 40 | 325 | .25 |
| Fine to coarse sand | Barnstable 253 | 41 38 42 | 70 19 23 | 9000 | 40 | 225 | .20 |
| Fine sand | Dennis 211 | 41 42 42 | 70 08 21 | 8000 | 30 | 270 | .17 |
| Fine to coarse-sand | Yarmouth 129 | 41 40 22 | 70 14 19 | 12000 | 55 | 220 | .17 |
| Medium sand | Harwich 128 | 41 41 09 | 70 02 06 | 12000 | 40 | 295 | .08 |
| Medium to coarse sand | Dennis 225 | 41 42 53 | 70 08 25 | 12000 | 65 | 185 | .23 |
| do. | Falmouth 177 | 41 35 44 | 70 32 04 | 18000 | 50 | 360 | .12 |
| Medium to coarse sand, gravel | Sandwich 282 | 41 42 04 | 70 44 28 | 32000 | 100 | 320 | .12 |

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sand. The exceptionally high value of horizontal hydraulic conductivity of 380 ft/day at well site Falmouth 214 reported by LeBlanc and others (1988) may be the result of a particularly uniform sediment of fine to medium sand with little percentage of other grain sizes.

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Tables 1 and 2--near here

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Very little aquifer test information is available for the moraine and glacio-lacustrine deposits because most of the previous aquifer tests were conducted in the sand and gravel outwash deposits. Estimates of horizontal hydraulic conductivity for glacio-lacustrine deposits were reported by Barlow (written commun., 1992) using permeameter analyses. The horizontal hydraulic conductivity of these deposits varied depending on the percent clay present in the sample, however, they were 3 to 5 orders of magnitude less than the sand and gravel deposits as shown in table 1.

Estimates of specific yield, specific storage, and storage coefficient have been made at only a few locations on Cape Cod. The storage coefficient is equal to the specific storage of the aquifer multiplied by its saturated thickness. Analysis of aquifer tests at well site TSW- 200 by Guswa and Londquist (1976) and site Orleans 37 by Guswa and LeBlanc (1985) indicate specific yields of 0.10 and 0.15, respectively. Palmer (1977, p. 45) reports a range of specific yield of 0.13 to 0.26 based on four aquifer tests in Falmouth. Garabedian and others (1988) report a range in specific yield of 0.1 to 0.2 and a range of specific storage of $4.4 \times 10^{-5}$ to $8.7 \times 10^{-5}$ ft-1 from the analysis of an aquifer test at well site Falmouth 214. Dufresne-Henry (1990, p. 13) reports a range of specific yield of 0.13 to 0.21 for an aquifer test at a well site in Mashpee. Finally, Barlow and Hess (P.M and K.M., U.S. Geological Survey, written commun.,1992) report a specific yield of 0.25 and a specific storage of $1 \times 10^{-6}$ ft-1 determined by analysis of an aquifer test at Mashpee well site MIW- 108. They determined a storage coefficient of $2 \times 10^{-4}$ for the aquifer at this site by assuming a saturated thickness of the aquifer of 210 ft near the pumped well. These estimates of the specific yield of Cape Cod sediments are similar to those reported for similar glacial sediments of Long Island, N.Y., of 0.10 to 0.26 (Linder and Reilly, 1983, Getzen, 1977, Perlmutter and Geraghty, 1963).

Porosity has been estimated for outwash near two well sites in Falmouth by means of ground-water tracer experiments and laboratory tests of cored sediments from the outwash. Estimates of porosity from the tracer tests range from 0.38 to 0.42 (Garabedian and others, 1988, p. 163; LeBlanc and others, 1988, p. B7; Barlow, 1989, p. 327), whereas that of the cored samples was 0.32 (Wolf, 1988, p. 106). The lower porosity reported by Wolf may have resulted from compaction of the cored samples. Porosity has also been deter-

mined for fine-medium sand in the town of Orleans. An average porosity of 0.34 was determined for 5 samples by means of laboratory volumetric measurements of cored samples (L.A. DeSimone, U.S. Geological Survey, personal commun., 1992). These several estimates of porosity are similar to those of 0.34 to 0.38 reported for the glacial outwash on Long Island, N.Y. (Perlmutter and Leiber, 1970).

## Analysis of Aquifer Tests

Horizontal hydraulic conductivity and specific yield of the glacial outwash were estimated by analysis of ten aquifer tests in the West Cape and East Cape flow systems. These analyses were made to increase the number of estimates for these parameters determined by use of aquifer tests in the flow system, such that estimates of horizontal hydraulic conductivity and specific yield can be made based on lithology at sites where no aquifer test information is available. Data used in the analysis were from engineer's reports of aquifer tests done as part of the process for developing a new water supply.

The Jacob-Cooper semi-logarithmic approximation to the Theis solution of radial flow to a well was used in the analysis (de Marsily, 1986, p. 163-165). The following assumptions were required for use of this method (de Marsily, 1986, p. 164-165): (1) the aquifer is infinite, homogeneous, and isotropic, (2) the aquifer is unconfined and drawdowns are small relative to the saturated thickness of the aquifer, (3) hydraulic head does not vary in the vertical direction and water velocity is parallel to a horizontal, impermeable bedrock boundary, and (4) the pumped and observation wells fully penetrate the aquifer, the pumping rate of the well is constant, and the borehole radius of the pumped well is negligibly small. Although several of these assumptions were not strictly met during the tests, the Jacob-Cooper method is a widely applied analysis technique that provides good initial estimates of horizontal hydraulic conductivity and specific yield for calibration of the flow models. In the technique, drawdowns at an observation well were plotted against the logarithm of time. Transmissivity and specific yield are then estimated from:

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$$T = \frac{2.3Q}{4\pi\Delta s} \tag{1}$$

and

$$S_y = \frac{2.25Tt_0}{r^2} \tag{2}$$

where $T$ is transmissivity (L /T),

$Q$ is pumping rate of the well (L /T),

$\Delta s$ is change in drawdown (L) over one logarithmic time cycle (for example, between time equal 100 minutes and time equal 10 minutes),

$Sy$ is specific yield,

$t_0$ is intercept along logarithmic time axis (that is, drawdown equal to zero) of straight-line portion of drawdown versus time curve, and

$r$ is distance of observation well from pumped well.

A complete description of the methodology of the Jacob approximation is provided by de Marsily (1986, p. 163-165). To apply these equations to the analysis of unconfined flow conditions, measured drawdowns were replaced by corrected drawdowns (Kruseman and de Ridder, 1983, p. 107):

$$s' = s' - (s^2/2b) \tag{3}$$

where $s'$ is corrected drawdown (L),

$s$ is uncorrected drawdown (L), and

$b$ is the saturated thickness of the aquifer (L).

In applying equations 1 and 2 to the analysis of the aquifer tests, the relation between the corrected drawdowns and logarithm of time must be linear. The following criteria were used to determine the time since pumping began after which equations (1) and (2) were assumed valid:

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$$0.02 \geq \frac{r^2 S_y}{4\pi t} \tag{4}$$

or,

$$t \geq \frac{r^2 S_y}{4T\,(0.2)} \tag{5}$$

where t is time since beginning of the aquifer test. This condition is met when either r is small or t is large. An upper limit of 0.02 was chosen for the analysis because de Marsily (1986, p. 164) states that the error between the Jacob approximation and the Theis solution, on which equations 1 and 2 are based, is 0.5 percent for the 0.02 limit. Although a value of 0.01 is commonly used, the difference in error between using a value of 0.01 and 0.02 is only 0.2 percent (de Marsily, 1986, p. 164), whereas the use of the higher criterion halves the time after which the approximation is valid thus increasing the number of valid aquifer test results. Two additional criteria were used to minimize the effect of partial penetration of the pumped and observation wells to the parameter estimates. These criteria are (Neuman, 1974, p. 309):

$$r \geq \frac{b}{\sqrt{\frac{K_v}{K_h}}} \tag{6}$$

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and

$$t \geq \frac{10 S_y r^2}{T} \tag{7}$$

where b is saturated thickness of the aquifer near the well (L),

Kv is vertical hydraulic conductivity of the aquifer (L/T), and

Kh is horizontal hydraulic conductivity of the aquifer (L/T).

These two criteria were adopted based on the results of Neuman (1974, p. 309) who found that the effect of partial penetration on drawdown in an unconfined aquifer disappears completely at distances from the pumped well greater than (b/ Kv/Kh) at times greater than ($10Syr^2/T$). A ratio of (Kz/Kh) of 1:3-1:5 for medium to coarse sand and gravel and of 1:30 for fine sand were assumed for equation 5 and are based on the results of table 1.

Horizontal hydraulic conductivity was determined by dividing the calculated transmissivity by the saturated thickness of the aquifer at or near the site of the aquifer test. Because the pumped and observation wells never fully penetrated the aquifers, a saturated thickness had to be estimated from available information. In this investigation, the saturated thickness of the aquifer was taken to be the distance from the water table to an assumed impermeable boundary at the contact between overlying sand and gravel sedi-

ments and underlying fine-grained sediments, such as silt and clay. It was assumed that the fine-grained sediments act as confining units that do not yield water to the overlying sand and gravel sediments during the aquifer tests.

Although 22 aquifer tests were analyzed using the above methodology, only the 10 reported here satisfied the three criteria of equations 5, 6, and 7 and had sufficient information to determine a reasonable estimate of the saturated thickness of the aquifer near the pumped well. Horizontal hydraulic conductivities determined by the 10 analyses (table 2) are similar to those determined by previous investigators, and horizontal hydraulic conductivity tends to increase with increasing grain size. Horizontal hydraulic conductivity estimated at sites Yarmouth 74 (180 ft/d) and Yarmouth 129 (220 ft/d) are within 13 percent of those determined by Barlow (U.S. Geological Survey, written commun., 1990) by means of a more complex analysis method in which dimensionless drawdown-versus-time type curves were developed for each pumped and observation well pair (Neuman, 1974). The strong correlation between the hydraulic conductivities determined by each of the two methods indicates that the Jacob approximation and three criteria used in this investigation appear to be a good estimation method for hydraulic conductivity.

Estimates of specific yield are generally more variable than those of hydraulic conductivity (see p. 46). Estimates range from 0.02 to 0.25 and are highest for fine to medium sand and gravel through medium to coarse sand. The average value of specific yield determined for the 10 tests is 0.15.

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Tables 3 to 5--near here
Figures 6 and 7-- near here

Seasonal fluctuations in ground-water use are due to the substantial population increases during the summer months of June, July and August, resulting in summer-season withdrawals that nearly double the winter-season withdrawals. It was assumed that 10 percent of the total ground-water withdrawals are lost to the aquifer system due to human consumption. The remaining 90 percent is returned to the aquifer system as returnflow from either infiltration beds at sewage treatment plants or residential septic systems.

Nearly 10 percent of the current withdrawals from public supply are returned to the aquifer as treated effluent at four sewage treatment plants on the Cape. The vast majority of the Cape Cod basin is not sewered and therefore most of the returnflow-recharge occurs at residential septic and cesspools systems. In the unsewered areas of the West Cape and East Cape flow cells, the returnflow was distributed based on the percent of the total road coverage length for each water district within each model block. The returnflow for sewered areas was concentrated at the location of the waste water-treatment plant infiltration beds. It was assumed that there was no other returnflow in the sewered areas and that leakage along sewer lines was negligible. The Truro flow cell differed from East Cape and West Cape because the majority of the ground-water withdrawals from Truro were supplied to the residents of Provincetown and were therefore lost to the aquifer system. Returnflow recharge is discussed in more detail in the section on "Model Stresses" for the West Cape and East Cape flow cells.

Agricultural and industrial withdrawals have not been considered in this study because (1.) they represent a small percent of the total ground-water withdrawals; (2.) daily withdrawal information for withdrawals less than 100,000 gal per day is not readily available: (3.) agricultural withdrawals are typically returned within the same model blocks from which they are pumped and therefore the net water lost to the system is minor.

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## West Cape and East Cape Flow Cells

The West and East Cape flow cells are the largest of the six flow cells of Cape Cod. Flow models developed for the West Cape flow cell extend from the Cape Cod Canal eastward to the Bass River and from Cape Cod Bay southward to Nantucket Sound (fig. 2). Flow models for the West Cape flow cell include the towns of Bourne, Sandwich, Falmouth, Mashpee, Barnstable, and most of Yarmouth. Flow models developed for the East Cape flow cell adjoin the eastern edge of the West Cape Flow models and extend from the Bass River in Dennis eastward to Town Cove and Rock Harbor in Orleans, and from the Cape Cod Bay southward to Nantucket Sound (fig. 2). Flow models for the East Cape flow cell include a small part of Yarmouth and all of the towns of Dennis, Brewster, Harwich, Chatham, and Orleans.

### Modeling Approach

The analysis of changing stress conditions within the West and East Cape flow cells consisted of two modeling phases. Within each phase, two flow models (a SHARP freshwater-saltwater flow model and a MODFLOW freshwater flow model) were developed for each flow cell. The first phase made use of the model hydraulic property data sets developed for the two flow cells by Guswa and LeBlanc (1985). The result of this was a preliminary assessment of the effect of changing stress conditions to the flow systems, and, in particular, an initial estimate of the movement of the interface between freshwater and saltwater in the two flow systems. This estimate of the freshwater-saltwater interface position and discharge of freshwater to overlying saltwater-saturated zones of the aquifer was used for boundary conditions in the MODFLOW models for each flow cell. Details on the conversion of the freshwater-saltwater interaction calculated by the SHARP models for boundary conditions for the MODFLOW models are discussed under "Simulation of the freshwater flow cells".

The hydraulic property data sets used in the first phase of the model were then modified based on hydrogeologic data made available since the work of Guswa and LeBlanc (1985). MODFLOW models were used in the calibration process. Initial estimates of hydraulic properties of the model were adjusted such that observed and calculated ground-water levels, pond levels, and streamflows were approximately equal.

Once the MODFLOW models of the first phase were modified using the new data and calibrated against actual measured head and streamflow measurements, a second phase (or second iteration) was used for the final assessment of the effects of changing stress conditions within the flow cells. The location of the freshwater-saltwater interface and discharge of freshwater to overlying saltwater that was calculated by use of the SHARP models provided criteria for determining the boundary conditions for the MODFLOW models. A third phase (or third iteration) of SHARP and MODFLOW simulations was not necessary because small changes made to the data sets of the MODFLOW models had very little effect on the movement of the freshwater-saltwater interface or of freshwater discharge to overlying saltwater.

Because the first phase was simply used as an initial iteration, the remainder of the discussion on the West and East Cape freshwater-saltwater and freshwater models refers only to the second phase of the modeling approach. Some components of the SHARP and MODFLOW models are common to both models. These are the horizontal discretization of the model grids, model hydraulic properties, and most of the stress conditions. Common elements to both the SHARP and MODFLOW models are discussed prior to the simulation of the freshwater-saltwater and freshwater flow systems.

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## Model grids

The finite-difference grids of the two flow systems consist of uniform cells of 1,320 ft by 1,320 ft. These cells are one quarter the size of those used by Guswa and LeBlanc (1985) and were necessary in order to improve the numerical stability of the freshwater-saltwater flow models (Essaid, 1990, p. 54). The West Cape grid consists of 72 rows and 118 columns (fig. 12). The East Cape grid consists of 50 rows and 74 columns (fig. 13).

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Figures 12 and 13--near here

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Each model consists of 5 layers (table 8). The vertical spacing of the models is similar to that used by Guswa and LeBlanc (1985). Changes were made to the vertical discretization of the original models, however, for three reasons. First, the bottom altitude of the top layer and the top altitude of the second layer of each freshwater model was set equal to pond-bottom altitudes for grid cells that underlie ponds that were represented in the freshwater models. Second, as discussed in greater detail under "Simulation of the freshwater flow cells", some grid cells were reduced in thickness to account for that part of the aquifer that was

Table 8.--*Vertical layering, horizontal hydraulic conductivity, and vertical conductance of calibrated saltwater-freshwater and freshwater flow models of the West Cape and East Cape flow cells*

[NGVD, National Geodetic Vertical Datum; --, vertical conductance was not specified for the bottom layer of either model]

| Model layer | Maximum depth of layer, in feet below NGVD of 1929 | Horizontal hydraulic conductivity in feet per day | Vertical conductance, in $day^{-1}$ |
|---|---|---|---|
| | | West Cape Flow Cell | |
| 1 | 20 | 3-250[1] | 0.0005-0.080 |
| 2 | 70 | 1-200 | .001-.068 |
| 3 | 140 | 1-150 | .001-.280 |
| 4 | 240 | 10-125 | .0001-.034 |
| 5 | 500 | 1-30 | -- |
| | | East Cape Flow Cell | |
| 1 | 20 | 3-250[1] | 0.00002-0.8000 |
| 2 | 70 | 1-150 | .0013-.044 |
| 3 | 140 | 10-75 | .002-.060 |
| 4 | 240 | 10-75 | .00001-.050 |
| 5 | 500 | 1-30 | -- |

[1]Grid cells underlying ponds represented in the models were assigned a horizontal hydraulic conductivity of 50,000 feet per day.

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shown by the SHARP models to be saturated with saltwater. Finally, modifications were made to the interpretation of the altitude of the bedrock surface, and were made to reflect lithologic data collected since the work of Guswa and LeBlanc (1985).

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Table 8--near here

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## Model hydraulic properties

Horizontal hydraulic conductivity and vertical conductance (referred to as vertical leakance in the freshwater-saltwater models) were determined for the models by comparing lithologic logs of test holes shown in cross section in figure 5 to values of hydraulic conductivity generalized for individual grain sizes from the results of the aquifer-test analyses reported earlier. The generalized values of horizontal hydraulic conductivity used were 150 ft/day for fine sand, 220 ft/day for medium sand, 350 ft/day for coarse sand, and 400 ft/day for very coarse sand. Silt and clay were assigned horizontal hydraulic conductivities of $1 \times 10^{-3}$ ft/d, which is the average value reported by Barlow (U.S. Geological Survey, written commun., 1992) for permeameter tests of silt and clay cored samples from Eastham. Vertical conductance between vertically adjacent nodes was calculated according to the following equation (McDonald and Harbaugh, 1988, p. 5-11):

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$$Vcont(K+\frac{1}{2}) = \frac{1}{\sum_{i=1}^{n} \frac{b_i}{Kv_i}} \qquad (8)$$

where

Vcont(k+1/2) is the vertical conductance between layers k and k+1, in $day^{-1}$,

Kv*i* is vertical hydraulic conductivity of the ith hydrogeologic unit between layers k and k+1, in feet per day;

b*i* is the thickness of the ith hydrogeologic unit between layers k and k+1, in feet; and

n is the number of hydrogeologic units between layers k and k+1.

Values of vertical hydraulic conductivity for different grain sizes were based on the ratios of horizontal to vertical hydraulic conductivity reported from analyses of aquifer and permeameter tests of the glacial sediments of Cape Cod (Guswa and Londquist, 1976, Guswa and LeBlanc, 1985, LeBlanc and others, 1988,

P.M., Barlow, U.S. Geological Survey, written commun., 1992, and P.M. Barlow and K.M. Hess, U.S. Geological Survey, written commun., 1992). The values used were 30:1 for fine sand and 5:1 for grain sizes larger than fine sand (medium, coarse, and very coarse sand and all gravel). A ratio of 1:1 was used for silt and clay and is based on permeameter tests of cored samples from Eastham (P.M. Barlow, U.S. Geological Survey, written commun., 1990).

Zones of geologically-similar deposits were defined using the lithologic logs and geologic maps of the study area (Oldale and Barlow, 1986). Uniform values of hydraulic conductivity and vertical conductance were used for each zone. Table 8 is a summary of the calibrated values that were determined for the final phase, calibrated models. In general, calibrated model values are less than initial estimates.

A uniform value of 0.16 for specific yield of was specified in the models; it was based on the results of the aquifer-test analyses reported in table 2. A uniform value of the storage coefficient of $2 \times 10^{-4}$ was used for both flow models, and was based on the work of Barlow and Hess (U.S. Geological Survey, written commun., 1992). Porosity, which is required for the SHARP models but was not required for the MODFLOW models, was specified at 0.3.

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## Model stresses

Four stress conditions were evaluated. They were: (1) steady-state ground-water-flow conditions assumed to correspond to conditions prior to 1950 in which there was no ground-water development in the flow systems (predevelopment conditions); (2) those similar to the period 1950-81, using pumping and recharge conditions of 1975-76; (3) those similar to the period 1982-2004, using pumping and recharge conditions of 1989; and (4) those similar to the period 2005-20, using pumping and recharge conditions equal to those expected for 2020. These four pumping and recharge stress conditions were an approximation of the true stress conditions that have increased, and are assumed to continue to increase, incrementally over time. These approximations were assumed to be sufficient for a regional analysis of changing stress conditions that have occurred in the flow system.

Pumping-well locations and pumping rates for 1975-76 were reported by Guswa and LeBlanc (1985) and pumping-well locations and pumping rates for 1989 were obtained from public-water suppliers of Cape Cod. Projected pumping rates for 2020 were obtained from MOWR, and projected pumping rates are based on 1989 estimates of future water needs for each flow cell by the year 2020.

Public-supply well locations and pumping rates for the three stress conditions are summarized in tables 3 and 4 and well locations are shown in figures 6 and 7. Total pumping from the West Cape flow cell increased from 10.9 Mgal/d in 1975-76 to 15.6 Mgal/d in 1989, and is anticipated to increase to 32.1 Mgal/d in 2020. Barnstable has had the overall largest volume of withdrawal in the past and is anticipated to have the largest increase (5.9 Mgal/d) in withdrawal between 1989 and 2020. Total pumping from the East Cape flow cell increased from 4.2 Mgal/d in 1975-76 to 7.3 Mgal/d in 1989, and is anticipated to increase to 14.4 Mgal/d in 2020. Dennis and Harwich have had the overall largest volume of withdrawal in the flow cell and are anticipated to have the largest withdrawals to 2020.

Recharge to the flow cells consists of precipitation and wastewater returnflow from sources such as septic systems and wastewater-treatment facilities. Recharge from precipitation was estimated for each of the flow systems by Guswa and LeBlanc (1985) using the method of Thornthwaite and Mather (1957). The estimated rates of recharge from precipitation were not changed during this investigation, with the exception that recharge rates were reduced at ponds to account for free-water-surface potential evaporation. Free-water-surface potential evaporation for ponds of Cape Cod is estimated to be 28 in/yr (Farnsworth and others, 1982, pl. 1). This value was subtracted from yearly precipitation rates in each flow cell to obtain net recharge rates beneath ponds of 16.8, and 15.0 in/yr, in the West Cape and East Cape flow cells, respectively. Precipitation recharge rates estimated using the Thornthwaite and Mather (1957) method were reduced by Guswa and LeBlanc (1985) in low-lying areas near the coast to account for increased rates of evapotranspiration by plants. Where the water table is close to land surface as in low-lying coastal swampy areas, more of the precipitation that infiltrates the soil may be transpired by plants or evaporated. Consequently, less rainfall recharges the aquifer than the areas with a thick or unsaturated zone. Precipitation recharge rates used in the models range from 6 to 22 in/yr in the West Cape and East Cape flow cells.

Wastewater return flow from septic systems was estimated for each cell of the upper layer of each model. Recharge rates from wastewater return flow for the period 1950 to 1982 were the same as those used by Guswa and LeBlanc (1985). Maps of public-water supply distribution lines and the average daily rate of water supplied to unsewered areas by water companies were used to determine wastewater return flow rates (Rt) for the 1975, 1989 and 2020 stress periods, according to:

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$$Rt = \left[\frac{Qwd}{Acell} \bullet \frac{Lcell}{Ltotal}\right] \bullet 0.9 \qquad (9)$$

in which

Qwd is the average daily rate of water distributed to unsewered areas by the water supplier in 1989 or 2020, in cubic feet per day;

Acell is the area of the grid cell, in feet squared;

Lcell is the length of roads within unsewered areas in the cell that are served by the water supplier, in feet; and

Ltotal is the total length of roads in unsewered areas that are served by the water supplier, in feet

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It was assumed that 10 percent of the water supplied to unsewered areas is lost by consumptive use. Recent data (M. Horn, U.S. Geological Survey, written commun., 1992), however, suggested that this value of consumptive use may be low, and that a more realistic value of consumptive use would be 15 percent. The difference between using a value of 10 percent and that of 15 percent (a maximum error of 1.5 percent of total recharge to each cell) is small compared to other sources of model error. Wastewater returnflow through septic systems accounts for no more than 30 percent of the total recharge to any grid cell in either model. No net recharge or discharge was simulated in areas serviced by both shallow domestic wells and onsite disposal systems, or in irrigated areas. Estimates of wastewater return flow for the three post-development stress periods (for the scale of the model grid cells) range from 0 to 6 in/yr in the West Cape flow cell and from 0 to 6 in/yr in the East Cape flow cell.

Water discharged to sewers is returned to the aquifers through infiltration beds at four wastewater-treatment facilities in the two flow cells (the Massachusetts Military Reservation facility in Sandwich, the Hyannis facility in Barnstable, and the Falmouth and Chatham facilities). Daily rates of wastewater infiltration at these four sites were obtained from plant personnel and distributed evenly in the grid cells of each model that contain the infiltration beds. Wastewater infiltration at these four facilities totals about 9 percent of the total volume of public-water supplies withdrawn from the flow cells in 1989.

## Simulation of the Freshwater and Saltwater Flow Systems

The SHARP model is a quasi-three-dimensional, finite-difference model that simulates coupled freshwater and saltwater flow in multilayered coastal systems (Essaid, 1990). In this study, each flow system is conceptualized as a single, unconfined system that may be locally semiconfined by confining units of low

hydraulic conductivity, such as glacio-lacustrine silt and clay deposits beneath Cape Cod Bay. In the flow models developed for the West Cape and East Cape flow cells there are no unrepresented confining units between vertically adjacent model cells, therefore, the entire thickness of the unconsolidated aquifers is simulated.

The SHARP model assumes that the freshwater and saltwater flow systems are immiscible fluids separated by a sharp interface, which implies that there is no transition zone between the freshwater and saltwater flow systems. This sharp-interface approximation is appropriate for the analysis of regional flow systems in which the width of the transition zone between the freshwater and saltwater is small relative to the thickness of the aquifer. A sharp-interface approximation was assumed for the West Cape and East Cape flow cells based on chloride concentration versus depth data measured at several well sites on Cape Cod that penetrate the transition zone (LeBlanc and others, 1986). Of 11 well sites reported by these authors at which the transition zone is completely penetrated, the zone of transition ranges from approximately 3 to 11 percent of the total saturated thickness of the aquifer at the site, and the mean thickness of the zone of transition at these 11 sites is 8 percent of the total saturated thickness.

Freshwater and saltwater specific gravities and viscosities were specified for the SHARP model. Values of 62.4032 and 64.057 lb/ft$^3$ for freshwater and saltwater specific gravity, respectively, and of $2.75 \times 10^{-5}$ (lbf)(sec)/ft$^2$ for freshwater and saltwater viscosities were specified in each of the models (Essaid, 1990).

<u>Boundary conditions</u>

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The models of the West Cape and East Cape flow cells are bounded on top by the water table, which is a free-surface boundary that receives spatially and temporally variable rates of recharge. Recharge rates specified for the models are discussed in the previous section "Model Stresses". The lower boundary of each model was the contact between the unconsolidated glacial sediments and underlying bedrock, which were assumed to be impermeable. Bedrock altitudes have been mapped in the two flow cells from available lithologic and seismic-refraction data by B.D. Stone (U.S. Geological Survey, unpublished data, written commun., 1990). Each model layer is bounded laterally by inactive cells that separate the modeled freshwater-saltwater flow systems from unmodeled areas (figs. 12 and 13).

Head-dependent flux boundary conditions were used to simulate saltwater discharge areas and freshwater streams. The head values specified at saltwater discharge boundaries were the freshwater heads equivalent to the column of saltwater overlying the seabed at the discharge boundary (Essaid, 1990, p. 53), and were determined according to:

$$Zf = \left[ \frac{(\rho_s - \rho_f)}{\rho_f} \right] Z_s \tag{10}$$

in which

| | |
|---|---|
| Zf | is the equivalent freshwater head, in feet; |
| Zs | is the distance from sea level to the seabed, in feet (from bathymetric maps of the area); |
| rhos | is the density of saltwater, assumed to be 1.025 grams per cubic centimeter; and |
| rhof | is the density of freshwater, assumed to be 1.000 grams per cubic centimeter. |

Saltwater head-dependent flux boundaries extend across the top two layers of each flow model--from 0 to 70 ft below sea level in the West Cape flow cell and from 0 to 40 ft below sea level in the East Cape flow cell. A vertical leakance term for the seabed deposits of 20 ft/d/ft, which was used by Guswa and LeBlanc (1985) and corresponds to a 1-ft thick sediment deposit on the seabed with a vertical hydraulic conductivity of 20 ft/d, was used in simulations reported here. Model results were not substantially affected by an order of magnitude of increase or decrease in the parameter.

Streams were also modeled as head-dependent flux boundaries. Heads specified at stream boundaries were estimated from topographic maps or, where available, from survey data. Streambed leakance was set at 0.2 ft/d/ft and was estimated from available data. Streams represented in the models are the Coonamessett, Childs, Quashnet, Mashpee, Santuit, and Centerville in the West Cape flow cell, and the Herring River and Stoney Brook in the East Cape flow cell.

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## Initial conditions and time steps

The West Cape and East Cape freshwater-saltwater flow cells were simulated for two steady-state stress conditions and one intervening transient-state stress condition (which corresponds to the years 1950-2020), according to the following procedure. First, a steady-state simulation was completed in which heads throughout the freshwater-saltwater flow system were calculated for conditions of no ground-water withdrawal (predevelopment conditions), assumed to have occurred until 1950. This was done by running the models over very long time periods until there was virtually zero change in storage within each model layer. This steady-state simulation was completed to determine heads and interface locations throughout the flow

cells that could be used as initial conditions for the transient simulation. This steady-state simulation also provided heads and interface locations, against which the effects of development conditions could be compared.

Once the predevelopment heads and interface locations were known, a transient simulation for the period 1950-2020 was completed. As discussed above, the 70-yr period was divided into three stress periods: 1950-81, 1982-2004, and 2005-2020. Once the transient simulation was completed, the models were again run to steady-state conditions using the 2020 proposed pumping and recharge rates. This simulation determined the ultimate distribution of heads and interface locations in each flow cell for the proposed 2020 pumping and recharge conditions.

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## Model calibration

In order to calibrate the two SHARP models, heads calculated by the SHARP models for 1975-76 pumping and recharge conditions were compared to observed heads measured at observation wells in each flow cell during the same period as reported by Guswa and LeBlanc (1985). Heads calculated from the models for the period 1975-76 were used in the comparison. the root mean squared error between calculated and observed heads for 32 observation wells in the West Cape flow cell was 1.5 ft, which corresponds to about 2 percent of the total drop in the altitude of the water table within the flow cell. The mean error between calculated and observed heads for 19 observation wells in the East Cape flow cell was 1.9 ft, which is about 4 percent of the total drop in altitude of the water table within the flow cell. In general, the calculated heads are lower (mean error of -0.57 for West Cape and -0.77 for East Cape) than observed heads.

Data reported by LeBlanc and others (1986) on the vertical location and shape of the freshwater-saltwater interface at 16 zone-of-transition well sites in the West Cape and East Cape flow cells was also used to compare model results with observed data. As discussed earlier, the SHARP model assumes a sharp interface between freshwater and saltwater. Each cell simulated in the SHARP model can consist completely of freshwater or saltwater, or can consist of freshwater in the top part of the cell and saltwater in the bottom part of the cell. In the latter case, the interface position between freshwater and saltwater within the cell was calculated by the model. For the first two cases, no interface position was calculated for the flow cell.

Eight zone-of-transition wells at which chloride data was collected were used per flow cell, and interface calculations from the SHARP models for the year 1976 were compared to the observed data, which was collected between January 1976 and April 1977. The vertical distribution of freshwater and saltwater determined by the SHARP models (figs. 14 and 15) in general agrees with the data presented by LeBlanc and oth-

ers (1986). Because saltwater cannot overlie freshwater within the same grid cell in SHARP models and because of the horizontal discretization used in the models, model results typically do not match the observed chloride data for conditions in which saltwater overlies freshwater in the top 20 ft of the aquifer (for example, wells DGW 168 and HJW 152-155, fig. 15). The use of a finer discretization near the coasts for each model might improve the simulation of the freshwater-saltwater interface in these cells. For the purpose of this study, however, in which the general response of the interface to changing stress conditions and an estimate of the location of the interface was sought, the overall agreement between observed and calculated interface locations at these 16 sites was sufficient.

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Figures 14 and 15--near here

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## Response of the Flow Cells to Changing Stresses

Very little change in the position of the freshwater-saltwater interface was observed to occur between the two steady-state simulations where pumping and recharge stresses were increased from predevelopment conditions to those anticipated to occur in 2020. For example, cross sections in the north-south direction showing the interface location along one column of each model, where there was substantial pumping, indicate little change in the position of the interface for increased pumping and recharge rates (fig. 16). Also, the volume of freshwater discharge to overlying saltwater-saturated zones of the aquifer did not change substantially with increased pumping and recharge rates. For example, the total volume of discharge from freshwater to overlying saltwater in layers 3 to 5 of the East Cape flow model only decreased slightly from 1.6 to 1.5 $ft^3/d$ for predevelopment to 2020 stress conditions. The volume of freshwater discharge decreased for the West Cape flow model. Increased ground-water pumping and recharge caused the volume of water moving through the upper three layers of each model to increase with time. As pumping rates increased, the volume of wastewater return flow also increases, and the total recharge to each system increased with time. Because only about 10 percent of the water pumped from the aquifer was actually lost from the system through consumptive use, the net stress on the system is small, and there is little encroachment of the freshwater-saltwater interface. Additionally, most of the septic system return flow occurs near the coasts, which helps to maintain the position of the interface.

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Figure 16--near here

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the freshwater-saltwater boundary and especially in the volume of discharge from freshwater to overlying saltwater, these stress conditions resulted in the most landward encroachment of the interface for the different stress conditions simulated. These conditions imply a conservatively small estimation of the volume of freshwater available for development.

## Boundary Conditions

A schematic figure illustrating the incorporation of the hydraulic dynamics along the freshwater-saltwater interface determined by the SHARP model and incorporated into the MODFLOW models is shown in figure 19. Lateral boundary conditions for the top two layers of the freshwater models are shown in figures 12 and 13. Grid cells completely filled with saltwater in the SHARP models were made inactive in the MODFLOW models. Grid cells partially filled with saltwater in the SHARP models (called mixed cells) were reduced in total thickness in the MODFLOW models to account for those parts of the aquifers containing saltwater. Freshwater discharge to overlying saltwater-saturated zones of aquifer in the bottom four layers of the SHARP models was removed from the MODFLOW models using pumping wells. The pumping rate of each of these wells was determined by subtracting the amount of freshwater arriving in an overlying cell from the amount of freshwater leaving from an underlying freshwater-containing cell. The total volume of discharge removed from each of the flow models in this manner was small (fig. 19) relative to the total volume of flow within each model, and some of this discharge, especially in the bottom three layers of each model, may in fact be attributed to model-solution errors caused by too coarse a horizontal discretization of the models.

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Figure 19--near here

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There was a close correlation in mass balance between the SHARP and MODFLOW models for the steady state 2020 pumping and recharge conditions using the methods discussed above. The volume rate of ground-water flow moving from the top to the bottom layers of the West Cape MODFLOW model ranged from 94 to 100 percent of the volume rate of flow moving from the top to the bottom layer of the West Cape SHARP model. The percentage ranged from 87 to 100 percent for the East Cape flow cell. Additionally, correlation of the volume rate of flow for the top three layers of each set of models was 99 to 100 percent for the

West Cape models and 93 to 100 percent for the East Cape models. Differences in the volume rate of flow between the SHARP and MODFLOW models results from errors introduced to the MODFLOW models through approximations made in the conversion from the SHARP models.

Freshwater discharge directly to saltwater bodies through seabed deposits in the top two layers of the SHARP models was simulated in the freshwater MODFLOW models using head-dependent flux boundary conditions. Freshwater heads specified at these boundaries were equal to an equivalent column of saltwater overlying the seabed at each boundary cell (equation 10) and were determined using bathymetric maps of the area. The leakance term between the flow cells and overlying column of saltwater was set to 20 ft/d/ft, to correspond to that used in the SHARP models.

Each of the freshwater models are bounded on top by the water table, which is a free-surface boundary receiving spatially and temporally variable rates of recharge. Recharge rates specified in the models were equal to those used in the SHARP models and discussed in the section "Model Stresses". In areas where freshwater is not underlain by saltwater, the lower boundary of each model is the contact between unconsolidated glacial sediments and underlying bedrock, which is assumed impermeable.

Freshwater streams were modeled as head-dependent flux boundaries. Streambed altitudes were specified for these boundaries and determined from topographic maps or from survey data. Streams represented in the models are the same as those represented in the SHARP models: the Coonamesset, Childs, Quashnet, Mashpee, Santuit, and Centerville in the West Cape flow cell and the Herring River and Stoney Brook in the East Cape flow cell.

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## Model Calibration

The West Cape and East Cape freshwater flow models were calibrated by comparison of calculated heads to measured heads at 62 well and pond locations in the West Cape flow cell and 49 well and pond locations in the East Cape flow cell (figs. 20 and 21). Comparison was also made of calculated streamflows to measured streamflows for the Coonamesset, Childs, and Quashnet Rivers in the West Cape flow cell and the Herring River in the East Cape flow cell. The flow models were calibrated to the average water levels in the Cape Cod observation wells measured between 1963 and 1976 for 1975 steady-state stress conditions. This time period was chosen because (1) there was no available observed water-level information for predevelopment conditions; (2) this time period is consistent with that used for model calibration by Guswa and Le Blanc (1985); (3) the water levels for this time period are representative of long-term average water levels reported in Letty (1984). Pond levels were read from topographic maps of the area and are considered to be

within 5 ft of the actual values. Observed streamflow information for Cape Cod is meager at best. The calculated streamflow for the 1975 steady-state stress condition was based for the most part upon the single discharge measurements reported in LeBlanc (1986). These measurements were obtained during the eriod of July 1978 to November 1979.

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Figures 20 and 21--near here

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Initial estimates of horizontal hydraulic conductivity and vertical conductance were adjusted during model calibration. Generally, agreement between observed and calculated heads is close at each of the observation points. The mean error between calculated and observed water levels in observation wells in the West Cape flow cell is 2.2 ft, or 3 percent of the total relief of the water table in the flow cell. The mean error between calculated and observed water levels in the East Cape flow cell is 2.2 ft, or 5 percent of the total relief of the water table in the flow cell. Total steady-state recharge to the two flow cells in 1975 is 248 $ft^3/s$ and 88 $ft^3/s$, which is 93 and 97 percent of the values calculated for the flow cells by Guswa and LeBlanc (1985).

A sensitivity analysis was conducted to determine the response of the calibrated West Cape and East Cape flow models to changes in recharge, horizontal hydraulic conductivity, vertical conductance, specific yield and storage coefficient. Each parameter was uniformly increased and decreased, while all others remained the same in order to determine the models' response to changes in that parameter. The response was reported as changes to the mean error of the absolute value of the difference between the observed and calculated heads at the observation wells shown in figures 20 and 21. The response of both the West Cape and East Cape flow models was similar and therefore only the West Cape was reported. Figure 22 shows that the flow models were most sensitive to increases and decreases in recharge and to decreases in the vertical conductance and horizontal hydraulic conductivity of the top model layer. Figure 23 shows that the models are more sensitive to increases than decreases in specific yield and storage coefficient. However, storage properties become less important with time at a given pumping rate. These results indicated that the uncertainty associated with each model parameter may have a significant effect on these flow models. The sensitivity analysis can identify those parameters to which model results are most sensitive, and guide future data collection toward better definition of those parameters.

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## Truro Flow Cell

The Truro flow cell is the smallest of the five flow cells of Cape Cod that are used for water supply, and is the only source of water for the communities of Truro and Provincetown. Freshwater enters the ground-water flow system at the water-table as recharge from precipitation, septic systems, and other wastewater sources. Ground-water flows radially outward from the potentiometric high at the center of the flow cell toward coastal discharge boundaries. The water-table elevation ranges from 0 ft at the coast to about 6 ft above sea level at the center of the peninsula. Ground-water discharge areas at Pilgrim Lake and Salt Meadow Marsh in the north and the Pamet River in the south separate the flow cell from the Province town flow cell to the north and the Wellfleet flow cell to the south. Ground-water also discharges to Cape Cod Bay to the west and the Atlantic Ocean to the east.

Although the sand and gravel aquifer extends to the bedrock, the freshwater flow system is bounded below by the transition zone between freshwater and the underlying saltwater (Guswa and LeBlanc,1985: LeBlanc and others,1986). Upconing of the freshwater-saltwater interface and contamination by saltwater encroachment caused by ground-water withdrawals have been recorded at the Knowles Crossing wellfield, located at a distance of 1,500 ft from Cape Cod Bay (LeBlanc and others, 1986).

## Modeling Approach

Evidence of saltwater upconing and encroachment precludes an assumption of a static interface between freshwater and saltwater and therefore, the freshwater flow model of McDonald and Harbaugh (1988) was not used for the analysis of changing stress conditions. The freshwater-saltwater flow model of Essaid (1990) was used to evaluate the Truro flow system.

The effect of changing stress conditions on the freshwater-saltwater flow system was determined by comparing changes in water-table elevation, water budget and the position and movement of the freshwater-saltwater interface. These were compared for predevelopment conditions, 1975, 1989 and 2020 stress conditions and under prolonged drought conditions. Water-table elevation changes were determined by comparing the heads in the observation wells used for the model calibration during the five stress conditions. Changes in the freshwater-saltwater interface position were determined by comparing the interface elevation below sea level at the locations shown in figure 32. These locations were chosen because they either (1) represent coastal or inland areas; (2) were the same locations reported by LeBlanc (1982) and results of the two investigations could be compared; (3) represented locations of public-supply wells in order to illustrate the effect of ground-water withdrawals on upconing. The changes in the water budget were determined by summing the inflows and outflows to the flow cell for each of the five stress conditions.

Figure 32--near here

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## Model grids

The modeled area extends from Pilgrim Lake to the Pamet River and distances offshore in order to include the near-shore saltwater flow system. The grid was three dimensional, with 26 columns and 20 rows and a uniform spacing of 1320 ft by 1320 ft. The grid has the same approximate orientation and extent as that used by Guswa and LeBlanc (1985) in their model of the Truro flow system. The aquifer was subdivided into 7 layers to provide an adequate vertical representation of the aquifer's lithology and to improve the stability for the solution of the freshwater- saltwater interface (as discussed in the previous section on "Simulation of the Freshwater-Saltwater Flow Systems"). The elevations and thicknesses of these layers are shown in table 24.

Table 24--near here

## Model hydraulic properties

The hydraulic parameters used in the discrete representation of the Truro aquifer system have been assigned based on available aquifer test information and on the lithology as it related to aquifer properties, as discussed in the previous section on "Aquifer Hydraulic Properties". There are very few deep wells in this

aquifer system, therefore, lithologic information necessary to determine hydraulic properties of the lower layers was limited. The hydraulic properties in areas with little or no lithologic information were assigned based on the interpretation of the geologic processes which formed the sand and gravel deposits in the Truro flow cell.

The hydraulic conductivity values ranged from 350 ft/day for sand and gravel to 50 ft/day for fine sands. The anisotropy of these glacial deposits ranged from 3: 1 for the sand and gravel and 30: 1 for the fine sands. The porosity of these deposits was assumed constant throughout the aquifer and equal to the value of 0.3, which had been used throughout the Cape Cod basin. Specific yield estimates for the Truro flow cell obtained from Guswa and LeBlanc (1985) were from 0.1 to 0.15. This range is consistent with the specific yield estimates in the section "Aquifer Hydraulic Properties". The storage coefficient for the lower layers was assumed to be 0.0002 as discussed earlier. During model calibration it was necessary to adjust the initial estimates of hydraulic conductivity and specific yield. Specific yield value of 0.1 was used in the calibrated model. The range in horizontal hydraulic conductivity and vertical conductance for each model layer are presented in table 24.

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## Model stresses

The effects of changing stress conditions on the Truro flow cell were determined for the predevelopment, 1975, 1989 and 2020 average daily demand stresses. The response of the flow cell to fluctuations between inseason and off-season in ground-water withdrawals and recharge was determined for current conditions based on the 1989 inseason and off-season pumping and recharge rates.

Predevelopment conditions assumed that there were no public-supply well withdrawals, aquifer recharge from precipitation equaled the average annual rate of 19.8 in/yr and that the change in storage was negligible. The resulting head distribution and freshwater-saltwater interface position from the predevelopment simulation was used as the initial condition for the subsequent transient simulations.

The 1975 stress condition assumed an average annual pumping rate from 1950 to 1981. The year 1950 was arbitrarily selected to represent the onset of large capacity public-supply well ground-water withdrawals in the Cape Cod basin. The actual date is insignificant because the system was at steady state (where change in storage equal to 0.) within several years after the onset of ground-water withdrawals. Aquifer recharge during the 1975 stress condition equaled the average annual recharge rate of 19.8 in/yr plus wastewater return flow from septic systems. The 1975 returnflow estimates for the Truro flow cell were based on a weighted average of the percentages of off-season and inseason ground-water withdrawals used in

North Truro. Assuming that 12 percent of the total withdrawals used to service North Truro for 9 months in the off-season and 25 percent of the total withdrawals for 3 months in the inseason, then the average annual returnflow is equal to 15 percent of the average annual ground-water withdrawals. The average annual 1975 pumping rate is equal to 0.91 Mgal/d. The return flow rate for the septage systems along route 6A equalled 90 percent of the 15 percent of the total pumping which equalled 0.12 Mgal/d.

The 1989 stress condition was simulated by off-season and inseason pumping periods. The off-season period was assumed to be from September through May. It was assumed that all of the annual natural recharge occurred during this 9 month period. The returnflow recharge was 90 percent of the 12 percent of the ground-water withdrawals distributed along Route 6A. The inseason pumping period simulated 3 months of summer pumping rates with no natural recharge. The only recharge to the system during the inseason pumping period was that distributed along Route 6A (fig. 33) which equalled 90 percent of the 25 percent of the total groundwater withdrawals. A 5-yr drought with a 30 percent reduction in natural recharge was simulated from 1989 to 1994 to determine the effects of a reduction in recharge on the water-table elevation and the position of the freshwater-saltwater interface. The projected stress condition for the 2020 was simulated based upon the projected average daily pumping rates supplied by the MOWR.

## Simulation of the Freshwater-saltwater Flow System

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### Boundary conditions

Natural boundaries of the flow system were used for model boundaries where possible. Ground-water discharge areas at Pilgrim Lake and the Pamet River to the north and south, respectively, were represented as specified-head boundaries in the model. These heads were determined from surface-water altitudes shown on the topographic maps. The small section along the northern boundary where the Truro flow cell and adjoining Provincetown flow cell meet, was designated a no-flow, or stream-surface boundary. Stream-surface boundaries were also used to separate the near-shore freshwater-saltwater flow system from the off-shore saltwater flow system. The locations of these boundaries did not affect model results, as shown by little change in the heads along these boundaries for each of the changing stress conditions.

Saltwater discharge areas in Cape Cod Bay and the Atlantic Ocean were represented as specified-head boundaries in the top three layers of the model, to a maximum depth of 70 ft below sealevel, as depicted in figure 33. The vertical locations of these specified-head boundaries correspond to the interface between the

aquifer and the seabed and were determined from of bathymetric maps of this area. Equivalent freshwater heads were determined for these specified-head cells using equation 10. Grid cells overlying these specified-head boundaries were inactive.

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Figure 33--near here

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The lower boundary of the model was the contact between unconsolidated glacial sediments and underlying bedrock, which was assumed to be impermeable. Bedrock altitudes have been mapped in the flow cell from available lithologic and seismic-refraction data by Byron Stone (U.S. Geological Survey, written commun., 1990).

The upper boundary of the model was the water table, a free-surface boundary that receives recharge from precipitation and wastewater return flow. Recharge at the water table was estimated at 19.8 in/yr by the method of Thornthwaite and Maher (1957), using 80 years of precipitation and air temperature data measured at the Provincetown weather station and an assumed soil-moisture capacity of the root zone of 4 in. This precipitation recharge estimate is consistent with others previously made for the Cape Cod flow system (LeBlanc, 1984; LeBlanc and others, 1986; P. M. Barlow, and K.M. Hess, U.S. Geological Survey, written commun., 1992). Wastewater return flow from septic systems was estimated for the area along Route 6A receiving water supplies from the Provincetown Water Department. The model nodes which received the waste-water returnflow within the Truro flow cell are shown in figure 33.

The volume of water supplied to the area along Route 6A is about 12 percent of the Water Department's total withdrawal during the winter and about 25 percent of the total in the summer (J. Cook, Provincetown Water Department, personal commun., 1992). Recharge rate from wastewater return flow was calculated by dividing total daily volume of water supplied to the areas by area of the grid cells where the water supply is distributed; to account for consumptive losses, it was assumed that only 90 percent of the total volume supplied to the areas was returned to the aquifer. Return flow from domestic and commercial septic systems in the areas not receiving water from the Provincetown Water Department was assumed to be equal to the amount of water withdrawn by wells at each site; therefore, net ground-water recharge from wastewater returnflow was assumed to be zero.

Freshwater ponds and streams are not as prevalent in the Truro flow cell as those of the West Cape and East Cape flow cells. Because of the size of the ponds in relation to the grid spacing and the negligible discharge rates from the streams, these surface water bodies were not simulated in this analysis.

## Model calibration

The initial estimates (as outlined in the "Aquifer Hydraulic Properties" section) of hydraulic properties used to define the glacial deposits in the Truro flow cell, were adjusted within the defined range for lithology type to provide the best match of the observed-head distribution for the measured observation wells within the flow cell. The average water-table elevations measured for the observation wells used in Guswa and LeBlanc (1985) for the period of 1963 to 1976 were used in the calibration of this model.

The location of the 12 wells used for the calibration of the Truro flow cell are shown in figure 32. The root mean squared error of the calculated heads is 0.3 ft. A maximum head in the flow cell of 7 ft was assumed, resulting in a mean error of 5 percent. The 5 percent error may be associated with the horizontal discretization and the location of the observation wells within the model cell, since the model-calculated head for a cell was in the center of the block and not all the observation wells are centered within each cell.

The position of the freshwater-saltwater interface for the 1975 stress conditions was compared to that of Guswa and Leblanc (1985) for the cross-section N-N' on figure 32. In figure 34, the position of the freshwater-saltwater interface is in close agreement between the two investigations. In addition, freshwater-saltwater interface projections were determined by Leblanc and others (1986) from chloride concentration changes, with depth, at the four locations in the Truro flow shown in figure 32. The comparison between the simulated freshwater-saltwater interface and those reported by LeBlanc and others (1986) are shown in figure 35.

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Figures 34 and 35-- near here

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## Response of Flow Cell to Changing Stress Conditions

The effects of changing stress conditions on the Truro aquifer system show that increases in ground-water withdrawals and (or) decreases in the aquifer recharge result in (1) reduction of discharge to coastal and subsea discharge boundaries; (2) reduction in water-table elevation; (3) decrease in the depth to the freshwater-saltwater interface.

Ground-water withdrawals from the Truro flow system generally increase from 1975 to 2020 due to the increases in population and development. As a result, water table elevations at the observation wells decline and the freshwater-saltwater interface position shows a decrease in depth below sea level. Table 25 shows the elevation of the water table for each stress condition and table 26 shows the changes in water-table ele-

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## Wellfleet and Eastham Flow Cells

### Modeling Approach

The analyses for the Wellfleet and Eastham flow cells were not as complex as those of East Cape, West Cape and Truro because (1) there were no existing or projected large capacity public-supply wells planned for these areas; (2) little hydrologic information has been developed for Wellfleet since Guswa and LeBlanc (1985), and for Eastham since Barlow (written commun., 1992) to significantly improve the existing flow models. A modular flow model was constructed for Wellfleet by updating the hydraulic input data sets and incorporating the freshwater-saltwater interface projection from Guswa and LeBlanc (1985) results. Barlow (written commun., 1992) recently constructed a modular flow model for Eastham using the available hydrologic information developed since Guswa and LeBlanc (1985).

The modular flow model was used for the analyses of Wellfleet and Eastham because it was assumed that the freshwater and saltwater flow systems were in equilibrium and the movement of the freshwater-saltwater interface was negligible in the absence of large-capacity ground-water withdrawals. The flow models were used to assess the effects of a long term drought on the water-table and water budget for each of the flow cells. These models were not developed to determine the response of the freshwater-saltwater interface to changing recharge conditions. The threat of saltwater encroachment contaminating a public supply source was not a concern in these flow cells.

#### Model grids

The Wellfleet modular model consists of 26 rows, 32 columns and 6 layers. The Wellfleet flow model reported in Guswa and LeBlanc (1985) had 7 layers. The lowest layer was not part of the freshwater flow system and was therefore not included in the modular model. The uniform grid spacing was 1320 by 1320 ft, with layers of variable thicknesses as shown in table 32.

Table 32.--*Vertical layering, horizontal hydraulic conductivity, and vertical conductance of the Wellfleet and Eastham flow cells for the calibrated freshwater models*

[The maximum depth, horizontal hydraulic conductivity, and vertical conductance of layer 5 of the Eastham flow model were not specified because transmissivity was used for the layer; --, vertical conductance was not specified for the bottom layer of the model; NGVD, National Geodetic Vertical Datum]

| Model layer | Maximum depth of layer, in feet below NGVD of 1929 | Horizontal hydraulic conductivity in feet per day | Vertical conductance, in $day^{-1}$ |
|---|---|---|---|
| | | Wellfleet flow cell | |
| 1 | 10 | 50-350[1] | 0.4-1.870 |
| 2 | 40 | 200-250 | .003-1.515 |
| 3 | 80 | 10-200 | .003-.286 |
| 4 | 140 | 10-100 | .003-.167 |
| 5 | 200 | 100 | .1430 |
| 6 | 280 | 100 | -- |
| | | Eastham flow cell | |
| 1 | 10 | 100-150[1] | 0.005-1.0 |
| 2 | 35 | 10-100 | .001-1.0 |
| 3 | 60 | .001-100 | .0001 |
| 4 | 90 | .001-100 | .00001 |

[1]Grid cells underlying ponds represented in the models were assigned a horizontal hydraulic conductivity of 50,000 feet per day.

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Table 32--near here

The three-dimensional flow model developed by Barlow (written commun., 1992) for the Eastham flow cell consisted of 96 rows, 78 columns and 5 layers. The vertical discretization was based on available information on the lithology of the glacial deposits. The two upper layers consisted of highly conductive sand and gravel deposits, two transitional layers consisted of both sand and gravel and silt and clay deposits, and a bottom layer consisted entirely of silt and clay. The horizontal discretization was finest in the areas of the hypothetical well sites to simulate the movement of water particles near these wells. Detailed discretization was not required for the purposes of this analysis. However, there was no justification for developing a less detailed model.

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## Model hydraulic properties

The aquifer properties used for the Wellfleet flow model were derived from estimating values of hydraulic conductivity from available lithologic logs as discussed earlier in "Aquifer Hydraulic Properties" section. Specific yield and storage coefficient values were estimated from the average values used in the East Cape and West Cape flow models. Specific yield was set at 0.16 for the top layer and 0.0002 was used as the storage coefficient for the lower, confined layers. The range in horizontal hydraulic conductivity and vertical conductance used in the Wellfleet flow model for each layer is presented in table 32.

The horizontal hydraulic conductivity and vertical conductance were determined for the Eastham flow model by comparing lithologic logs of test holes at 31 sites to generalized values developed by Barlow (written commun., 1992). The transmissivity of layer 5 was determined by multiplying the average hydraulic conductivity of the silt and clay determined by laboratory test at well ENW 45 by the total thickness of the layer. Specific yield and storage coefficient values were approximated, based on the values used for the flow models of East Cape and West Cape. Specific yield is equal to 0.16 for the top layer; storage coefficient of the lower layers was equal to 0.0002. The range in horizontal hydraulic conductivity and vertical conductance used in the Eastham flow model for each layer is presented in table 32.

## Model stresses

The simulations for the Wellfleet and Eastham flow cells were not as complex as those of the West Cape, East Cape and Truro due to the absence of large capacity public-supply well stresses. The water-supply needs of the residents of the towns of Wellfleet and Eastham were met by private wells. Wastewater is returned to the ground-water system by on-site septage systems; it was assumed that the net loss to the system is negligible.

Both flow cells were simulated for predevelopment steady-state conditions to determine the water budget and head distribution for long-term average recharge conditions. The results from these simulations were used as the initial conditions for the transient analysis, in which a 30-percent reduction in recharge was simulated for 5 years, as discussed for the West and East Cape freshwater flow models.

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# Simulation of Freshwater Flow Systems

## Boundary conditions

The Wellfleet flow cell is south of the Truro flow cell and north of the Eastham flow cell as shown in figure 2. The Pamet River represents the ground-water divide separating the Wellfleet and Truro flow cells. The Blackfish Creek forms the ground-water divide between Wellfleet and Eastham. Wellfleet is bounded on the west by the Cape Cod Bay and Wellfleet Harbor, and to the east by the Atlantic Ocean. The water-table elevation ranges from 7 ft above sea level at the center of the flow cell to near 0 ft at the shore. Under natural conditions, freshwater enters the ground-water system at the water-table as recharge from precipitation. Ground-water flows radially out from the potentiometric high at the center of the flow cell toward the coastal discharge boundaries. A series of small streams discharges to the Wellfleet Harbor. The unconsolidated sand and gravel aquifer of the flow cell extends to the impervious bedrock surface. However, results from Guswa and LeBlanc (1985) show that the freshwater lens is bounded below by the freshwater-saltwater interface at approximately 280 ft.

The boundaries for the Wellfleet flow model were determined from the previous investigation of Guswa and LeBlanc (1985). A No-flow (inactive) boundary was set at the natural southernmost ground-water divide between Wellfleet and Eastham, as discussed in Guswa and LeBlanc (1985). The Pamet River which forms the northern boundary of the flow cell was represented as a head dependent flux boundary.

Specified head cells were used in the top layer to simulate the saltwater bodies of Cape Cod Bay, Wellfleet Harbor and Atlantic Ocean. Although the movement of the freshwater-saltwater interface was not simulated, equivalent freshwater heads were used at the coastal saltwater boundaries to account for the higher density saltwater that overlies the freshwater system at the seabed discharge boundaries (fig. 42). The equivalent heads used in the Wellfleet model were obtained from Guswa and LeBlanc (1985) model input data.

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Figure 42--near here

The freshwater-saltwater interface position determined by Guswa and LeBlanc (1985) was used to determine the extent of the freshwater flow system in the modular flow model. The nodes determined to be part of the freshwater system were kept active, while those in saltwater were made inactive. All subsequent nodes below an overlying saltwater node were considered inactive in the lower layers. The freshwater-saltwater interface elevation represents the lowest extent of the freshwater flow system and was specified as a no-flow boundary based on the results of Guswa and LeBlanc (1985).

The upper boundary of the Wellfleet flow cell was the water-table surface, represented as a free surface with a specified flux of 19.8 in/yr. This recharge rate had been previously determined for the adjoining Truro flow cell. Nodes containing ponds were assigned a reduced recharge rate to account for evaporation at the pond surface. A series of small streams and wetlands intersect the water-table and drain the top layer, and discharging to the Wellfleet Harbor (fig. 43). These surface water bodies are ground-water fed and act as local sinks to the freshwater system. The discharge in these nodes was determined by the head in the stream and conductance between the streambed and the aquifer.

Figure 43--near here

The Eastham flow cell is south of the Wellfleet flow cell and north of the East Cape flow cell (fig. 2). Blackfish Creek forms the ground-water divide separating the Eastham and Wellfleet flow cells. Town Cove and Boat Meadow River represent the ground-water divide between Eastham and East Cape. Eastham is bounded on the west by Cape Cod Bay and to the east by the Atlantic Ocean and Nauset Harbor. The unconsolidated sands, silts and clays extend down to the bedrock surface which forms the lowest extent of the Eastham flow cell.

The general direction of ground-water flow is from the potentiometric high in the center of the flow cell toward the coastal discharge boundaries. The ground-water divides at the northern and southern borders of the flow cell prevent ground-water flow between adjoining flow cells.

The model boundaries for the Eastham three-dimensional flow model were determined by Barlow (written commun., 1992) and are shown in figure 44. Specified head cells were used to simulate saltwater bodies that surround much of the modeled area. Equivalent freshwater heads were used at coastal saltwater boundaries to account for the higher density saltwater that overlies the freshwater system at the seabed discharge boundaries. These specified head cells were only used in the top layer of the model. The cells in layers 2 through 5 underlying these cells remained active with the no-flow boundary used to represent the freshwater-saltwater interface in the adjacent seaward cells. No-flow boundaries were specified at the northern and southern extents of the flow model to coincide with the natural divides separating Eastham from Wellfleet and East Cape. The model was bounded above by a specified flux equal to the natural recharge rate of 17 in/yr and below by the no-flow boundary which represents the contact between glacial deposits and bedrock. Ponds simulated in the top layer were assigned a reduced recharge rate of 12.4 in/yr to account for evaporation losses from the pond surfaces.

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Figure 44--near here

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## Model calibration

The aquifer properties used in the Wellfleet flow model were calibrated by comparing the calculated water-table elevation at the five observation wells and five pond levels shown in figure 43. The water table elevations reported for the observation wells represent the average water levels from 1963 to 1976 which were used in Guswa and LeBlanc (1985) and are consistent with the calibration for the West Cape, East Cape, and Truro flow models.

Calibration of the freshwater model for the Eastham flow cell was conducted by comparing the calculated ground-water heads to observed heads and pond elevations at 22 locations in the flow cell taken from water level measurements taken in 1988 (fig. 45). For more detailed discussion on the calibration of the Eastham flow model, see Barlow (1992).

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Figure 45--near here

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## WEST CAPE MODEL WELLS

Updated dec 1992 - jan 1993, proposed pumping based on October - December 1992 interviews with water supply officials; 1988-90 pumping based on DEP water supply statistical report data.

| Barnstable Fire District | | | | Existing 88-90 pumpage | | Projected 2020 In Season Pumpage | | Projected 2020 Off Season Pumpage | | Projected 2020 Avg Annual Pumpage | | Pumping Capacity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth | Row | Col. | cfd | mgd | cfd | mgd | cfd | mgd | cfd | mgd | cfd | mgd |
| well 1. | 1 | 34 | 87 | 6684.5 | 0.05 | 21390.4 | 0.16 | 0.0 | 0.00 | 6912.7 | 0.07 | 57486.6 | 0.43 |
| well 2.(offline,rehab) | 2 | 38 | 90 | 17379.7 | 0.13 | 32085.6 | 0.24 | 22727.3 | 0.17 | 26626.6 | 0.20 | 114973.3 | 0.86 |
| well 3. | 2 | 36 | 84 | 29411.8 | 0.22 | 32085.6 | 0.24 | 22727.3 | 0.17 | 26626.6 | 0.20 | 153743.3 | 1.15 |
| p-well 4.(summer 93) | 2 | 36 | 83 | | — | 48128.3 | 0.36 | 22727.3 | 0.17 | 33311.1 | 0.25 | 106951.9 | 0.80 |
| p*-1776 well. | 1 | 34 | 76 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 66844.9 | 0.50 |
| | 5 nodes | | | | 0.40 | | 1.00 | | 0.51 | | 0.71 | | 3.24 |

| Barnstable Water Company | | | | Existing 88-90 pumpage | | Projected 2020 In Season Pumpage | | Projected 2020 Off Season Pumpage | | Projected 2020 Avg Annual Pumpage | | Pumping Capacity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth | Row | Col. | cfd | mgd | cfd | mgd | cfd | mgd | cfd | mgd | cfd | mgd |
| airport well 1.(r) | 2 | 41 | 92 | 69518.7 | 0.52 | 86898.4 | 0.85 | 70855.8 | 0.53 | 77540.1 | 0.56 | 192513.4 | 1.44 |
| hyannispt well, | | | | | | | | | | | | | |
| simmons pond well. | 2 | 48 | 84 | 127005.3 | 0.95 | 100267.4 | 0.75 | 84224.6 | 0.63 | 90909.1 | 0.68 | 231283.4 | 1.73 |
| maher wells 1,2,3. | 2 | 44 | 92 | 102941.2 | 0.77 | 211229.9 | 1.58 | 100267.4 | 0.75 | 146501.8 | 1.10 | 366310.2 | 2.74 |
| mary dunn wells 3,4.(r) | 2 | 39 | 91 | 28074.9 | 0.21 | 33422.5 | 0.25 | 13369.0 | 0.10 | 21724.6 | 0.18 | 192513.4 | 1.44 |
| mary dunn well 2,(r) | | | | | | | | | | | | | |
| p*-mary dunn well 7, | | | | | | | | | | | | | |
| p*-mary dunn well 8. | 2 | 39 | 92 | 40107.0 | 0.30 | 33422.5 | 0.25 | 34759.4 | 0.26 | 34202.3 | 0.26 | 135028.7 | 1.01 |
| mary dunn well 1.(r) | 1 | 36 | 91 | 8021.4 | 0.06 | 33422.5 | 0.25 | 13369.0 | 0.10 | 21724.6 | 0.16 | 96256.7 | 0.72 |
| p*-mary dunn wells 5,6. | 2 | 38 | 92 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 135028.7 | 1.01 |
| p*-airport well 2. | 2 | 40 | 91 | | — | | | | | | | | |
| straightway well1.(benzene) | 2 | 47 | 84 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 98258.7 | 0.72 |
| p-straightway well 2. | 2 | 46 | 84 | | — | 53475.9 | 0.40 | 34759.4 | 0.26 | 42557.9 | 0.32 | 192513.4 | 1.44 |
| p-myles/sydney. | 2 | 47 | 83 | | — | 69518.7 | 0.52 | 34759.4 | 0.26 | 49242.4 | 0.37 | 133689.8 | 1.00 |
| | 11 nodes | | | | 2.81 | | 4.85 | | 2.89 | | 3.62 | | 13.25 |

p- proposed source, included in model runs.

P*- proposed for future, not included in model runs.

(r) Use restricted by DEP, Water Management Act.

# WEST CAPE MODEL WELLS continued

| Centerville/ Osterville Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mcshane wells 1,2. | 2 | 46 | 67 | 6684.5 | 0.05 | 8021.4 | 0.06 | 4010.7 | 0.03 | 5681.8 | 0.04 | 307486.6 | 2.30 |
| arena well 3. | 1 | 45 | 67 | 5347.6 | 0.04 | 8021.4 | 0.06 | 4010.7 | 0.03 | 5681.6 | 0.04 | 96256.7 | 0.72 |
| arena well 4. | 2 | 45 | 67 | 6684.5 | 0.05 | 8021.4 | 0.06 | 4010.7 | 0.03 | 5681.8 | 0.04 | 96256.7 | 0.72 |
| lambert well 5. | 2 | 42 | 72 | 10695.2 | 0.06 | 13369.0 | 0.10 | 5347.6 | 0.04 | 8889.8 | 0.07 | 57486.6 | 0.43 |
| craigville wells 7,6,11. | 1 | 46 | 61 | 28074.9 | 0.21 | 42780.7 | 0.32 | 18716.6 | 0.14 | 28743.3 | 0.22 | 148395.7 | 1.11 |
| lambert well 9. | 1 | 42 | 72 | 36096.3 | 0.27 | 42780.7 | 0.32 | 16716.6 | 0.14 | 26743.3 | 0.22 | 92246.0 | 0.69 |
| davis well 10. | 1 | 45 | 66 | 28074.9 | 0.21 | 34759.4 | 0.26 | 14705.9 | 0.11 | 23061.5 | 0.17 | 81497.3 | 0.46 |
| murray wells 12,13. | 2 | 38 | 70 | 48126.3 | 0.36 | 60180.4 | 0.45 | 25401.1 | 0.19 | 39884.1 | 0.30 | 133689.8 | 1.00 |
| hayden wells 14,15,17. | 2 | 40 | 61 | 112299.5 | 0.84 | 137700.5 | 1.03 | 58923.5 | 0.44 | 91688.9 | 0.69 | 288770.1 | 2.16 |
| hayden well 16. | 1 | 39 | 61 | 0.0 | 0.00 | 41443.9 | 0.31 | 17379.7 | 0.13 | 27406.4 | 0.21 | 76203.2 | 0.57 |
| harrison well 18. | 1 | 31 | 64 | 57486.6 | 0.43 | 73529.4 | 0.55 | 30748.7 | 0.23 | 48574.0 | 0.36 | 135026.7 | 1.01 |
| harrison well 19. | 2 | 30 | 64 | 22727.3 | 0.17 | 97593.6 | 0.73 | 48128.3 | 0.36 | 68738.9 | 0.51 | 192513.4 | 1.44 |
| Hayden well 20. | 2 | 39 | 60 | | — | 64171.1 | 0.48 | 30748.7 | 0.23 | 44674.7 | 0.33 | 133689.8 | 1.00 |
| p-40-89 well. | 2 | 40 | 59 | | — | 64171.1 | 0.48 | 30748.7 | 0.23 | 44674.7 | 0.33 | 133689.8 | 1.00 |
| p-41-89 well. | 2 | 39 | 59 | | — | 64171.1 | 0.48 | 30748.7 | 0.23 | 44674.7 | 0.33 | 133689.8 | 1.00 |
| | 15 nodes | | | | 2.71 | | 5.69 | | 2.56 | | 3.86 | | 15.61 |

| Cotuit Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 2. | 1 | 45 | 57 | 12032.1 | 0.09 | 18716.8 | 0.14 | 8021.4 | 0.06 | 12477.7 | 0.09 | 96258.7 | 0.72 |
| well 1. | 2 | 45 | 57 | 13369.0 | 0.10 | 20053.5 | 0.15 | 8021.4 | 0.06 | 13034.8 | 0.10 | 96256.7 | 0.72 |
| well 3. | 1 | 48 | 57 | 10695.2 | 0.08 | 16716.6 | 0.14 | 8021.4 | 0.06 | 12477.7 | 0.09 | 77540.1 | 0.56 |
| well 4. | 1 | 44 | 57 | 14705.9 | 0.11 | 22727.3 | 0.17 | 10695.2 | 0.08 | 15708.6 | 0.12 | 96256.7 | 0.72 |
| p-well 7, route 130 well. | 3 | 43 | 53 | | — | 21390.4 | 0.16 | 9358.3 | 0.07 | 14371.7 | 0.11 | 231283.4 | 1.73 |
| | 5 nodes | | | | 0.38 | | 0.76 | | 0.33 | | 0.51 | | 4.47 |

| South Sagamore Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 232. | 2 | 5 | 48 | 13369.0 | 0.10 | 24064.2 | 0.18 | 13369.0 | 0.10 | 17825.3 | 0.13 | 44117.6 | 0.33 |
| | 1 node | | | | 0.10 | | 0.18 | | 0.10 | | 0.13 | | 0.33 |

p- proposed source, included in model runs.

# WEST CAPE MODEL WELLS continued

| Bourne Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 1a. | 2 | 19 | 26 | 20053.5 | 0.15 | 32085.6 | 0.24 | 12032.1 | 0.09 | 20387.7 | 0.15 | 96256.7 | 0.72 |
| well b. | 1 | 19 | 27 | 20053.5 | 0.15 | 32085.6 | 0.24 | 12032.1 | 0.09 | 20387.7 | 0.15 | 96256.7 | 0.72 |
| well 2. | 2 | 30 | 25 | 17379.7 | 0.13 | 17379.7 | 0.13 | 10695.2 | 0.08 | 13480.4 | 0.10 | 114973.3 | 0.86 |
| well 3. | 1 | 19 | 29 | 18716.6 | 0.14 | 21390.4 | 0.16 | 13369.0 | 0.10 | 16711.2 | 0.13 | 114973.3 | 0.86 |
| well 4. | 2 | 18 | 28 | 20053.5 | 0.15 | 25401.1 | 0.19 | 14705.9 | 0.11 | 19162.2 | 0.14 | 114973.3 | 0.86 |
| well 5. | 1 | 31 | 25 | 26074.9 | 0.21 | 68181.8 | 0.51 | 49465.2 | 0.37 | 57263.8 | 0.43 | 135026.7 | 1.01 |
| p-well 6. | 2 | 20 | 27 | | — | 66844.9 | 0.50 | 49465.2 | 0.37 | 56706.8 | 0.42 | 133689.8 | 1.00 |
| | 7 nodes | | | | 0.93 | | 1.97 | | 1.21 | | 1.53 | | 6.03 |

| Otis Air National Guard Base Water System | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well j(sandwich). | 1 | 33 | 40 | 53475.9 | 0.40 | 33422.5 | 0.25 | 42780.7 | 0.32 | 38881.5 | 0.29 | 259358.3 | 1.94 |
| p-11-2**. | 1 | 39 | 48 | | — | 44117.6 | 0.33 | 9358.3 | 0.07 | 23841.4 | 0.18 | 133689.8 | 1.00 |
| | 2 node | | | | 0.40 | | 0.58 | | 0.39 | | 0.47 | | 2.94 |

p- proposed source, included in model runs.

** proposed agreement to purchase up to 0.33 mgd from Mashpee,

Mashpee plans to use well p-11-2 to supply Otis.

# WEST CAPE MODEL WELLS continued

| Falmouth Water Department | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| long pond | 2 | 52 | 18 | 48128.3 | 0.36 | 89572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267379.7 | 2.00 |
| long pond | 2 | 53 | 18 | 48128.3 | 0.36 | 89572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267379.7 | 2.00 |
| long pond | 2 | 54 | 16 | 48126.3 | 0.36 | 69572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267379.7 | 2.00 |
| long pond | 2 | 55 | 18 | 48128.3 | 0.36 | 89572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267379.7 | 2.00 |
| long pond | 2 | 53 | 19 | 48128.3 | 0.36 | 89572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267379.7 | 2.00 |
| long pond. | 2 | 54 | 19 | 48128.3 | 0.36 | 89572.2 | 0.67 | 44117.6 | 0.33 | 63057.0 | 0.47 | 267378.7 | 2.00 |
| fresh pond well. | 2 | 51 | 35 | 100267.4 | 0.75 | 61550.6 | 0.61 | 81550.8 | 0.61 | 81550.8 | 0.61 | 133688.8 | 1.00 |
| coonamassett well. | 1 | 44 | 28 | 77540.1 | 0.58 | 93582.9 | 0.70 | 77540.1 | 0.58 | 84224.6 | 0.63 | 133689.8 | 1.00 |
| p-f6d well(marespondwell) | 2 | 50 | 23 | | — | 30748.7 | 0.23 | 26738.0 | 0.20 | 28409.1 | 0.21 | 53475.9 | 0.40 |
| p-f4d well(crookedpondwell) | 1 | 42 | 25 | | — | 66844.9 | 0.50 | 26738.0 | 0.20 | 43449.2 | 0.33 | 133689.8 | 1.00 |
| p*-f-f3 well. | 1 | 50 | 37 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |
| p-f-8a well.(rod&gun club) | 2 | 52 | 38 | | — | 66844.9 | 0.50 | 9358.3 | 0.07 | 33311.1 | 0.25 | 133689.8 | 1.00 |
| p*-beebe woods well. | 1 | 58 | 15 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |
| | 14 nodes | | | | 3.49 | | 6.56 | | 3.64 | | 4.86 | | 16.40 |

| Mashpee Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 1(wading). | 2 | 58 | 48 | 5347.6 | 0.04 | 12032.1 | 0.09 | 4010.7 | 0.03 | 7352.9 | 0.06 | 33422.5 | 0.25 |
| wells 2,3(rockland). | 2 | 59 | 46 | 40107.0 | 0.30 | 81550.8 | 0.61 | 22727.3 | 0.17 | 47237.1 | 0.35 | 267379.7 | 2.00 |
| well t-4. | 1 | 45 | 51 | 5347.6 | 0.04 | 34759.4 | 0.26 | 6684.5 | 0.05 | 18382.4 | 0.14 | 100267.4 | 0.75 |
| p-p-1 well. | 1 | 51 | 41 | | — | 34759.4 | 0.26 | 6684.5 | 0.05 | 18382.4 | 0.14 | 100267.4 | 0.75 |
| p-t-8 well. | 2 | 35 | 53 | | — | 44117.6 | 0.33 | 9358.3 | 0.07 | 23841.4 | 0.18 | 133689.8 | 1.00 |
| p-t-5 well. | 1 | 41 | 53 | | — | 46791.4 | 0.35 | 13368.0 | 0.10 | 27295.0 | 0.20 | 66844.9 | 0.50 |
| p-holland mill well. | 1 | 52 | 46 | | — | 80213.9 | 0.60 | 18716.6 | 0.14 | 44340.5 | 0.33 | 133689.8 | 1.00 |
| | 7 nodes | | | | 0.38 | | 2.50 | | 0.61 | | 1.40 | | 6.25 |

p- proposed source, included in model runs.

P*- proposed for future, not included in model runs.

note: Mashpee is developing well p-11-2 to supply

Otis Air National Guard Base Water Supply.

# WEST CAPE MODEL WELLS continued

| Sandwich Water District | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 2,3. | 2 | 13 | 56 | 80213.9 | 0.60 | 57486.6 | 0.43 | 44117.6 | 0.33 | 49688.1 | 0.37 | 192513.4 | 1.44 |
| p-well 1.(emerg. only) | 2 | 6 | 52 | | — | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 | 49465.2 | 0.37 |
| pinkham wells 4,6,p-10. | 2 | 25 | 55 | 61497.3 | 0.46 | 140374.3 | 1.05 | 72192.5 | 0.54 | 100601.6 | 0.75 | 401069.5 | 3.00 |
| well 5. | 1 | 29 | 42 | 21390.4 | 0.18 | 28074.9 | 0.21 | 22727.3 | 0.17 | 24955.4 | 0.19 | 133689.8 | 1.00 |
| hog pond/hollyrg well 8. | 2 | 29 | 57 | | — | 52139.0 | 0.39 | 46791.4 | 0.35 | 49019.8 | 0.37 | 133689.8 | 1.00 |
| nye pond well 7. | 2 | 20 | 63 | | — | 52139.0 | 0.39 | 37433.2 | 0.28 | 43560.6 | 0.33 | 133689.8 | 1.00 |
| boiling spring well 9. | 1 | 13 | 56 | | — | 53475.9 | 0.40 | 37433.2 | 0.28 | 44117.6 | 0.33 | 133689.8 | 1.00 |
| | 7 nodes | | | | 1.22 | | 2.87 | | 1.95 | | 2.33 | | 8.81 |

| Yarmouth Water Department | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| main sta.&p*-union st.wells. | 2 | 35 | 104 | 42780.7 | 0.32 | 131016.0 | 0.98 | 58823.5 | 0.44 | 89903.7 | 0.67 | 192513.4 | 1.44 |
| well 1,2,3. | 2 | 38 | 97 | 16042.8 | 0.12 | 88235.3 | 0.66 | 26738.0 | 0.20 | 52361.9 | 0.39 | 195187.2 | 1.46 |
| well 4,5. | 2 | 43 | 107 | 28074.9 | 0.21 | 104278.1 | 0.78 | 37433.2 | 0.28 | 85285.2 | 0.49 | 133689.8 | 1.00 |
| well 6,7,8,9. | 2 | 40 | 112 | 65508.0 | 0.49 | 208556.1 | 1.56 | 65508.0 | 0.49 | 125111.4 | 0.94 | 259358.3 | 1.94 |
| well 10. | 2 | 41 | 104 | 14705.9 | 0.11 | 42780.7 | 0.32 | 21390.4 | 0.16 | 30303.0 | 0.23 | 57486.8 | 0.43 |
| well 11. | 2 | 42 | 104 | 14705.9 | 0.11 | 42780.7 | 0.32 | 21390.4 | 0.16 | 30303.0 | 0.23 | 57486.6 | 0.43 |
| well 13.(r) | 2 | 42 | 100 | 24064.2 | 0.18 | 40107.0 | 0.30 | 37433.2 | 0.28 | 38547.2 | 0.29 | 88898.4 | 0.85 |
| well 14.(r) | 2 | 43 | 97 | 18716.6 | 0.14 | 33422.5 | 0.25 | 32085.6 | 0.24 | 32642.8 | 0.24 | 86844.9 | 0.50 |
| wells 15,18. | 2 | 37 | 110 | 42780.7 | 0.32 | 168449.2 | 1.26 | 54812.8 | 0.41 | 102161.3 | 0.76 | 192513.4 | 1.44 |
| well 17.(r) | 2 | 43 | 98 | 28074.9 | 0.21 | 48128.3 | 0.36 | 37433.2 | 0.28 | 41889.5 | 0.31 | 114973.3 | 0.86 |
| wells 18(r),19(r). | 2 | 43 | 100 | 45454.5 | 0.34 | 77540.1 | 0.58 | 64171.1 | 0.48 | 69741.5 | 0.52 | 173796.8 | 1.30 |
| well 20. | 2 | 39 | 97 | 16042.8 | 0.12 | 61497.3 | 0.46 | 28738.0 | 0.20 | 41221.0 | 0.31 | 66844.9 | 0.50 |
| well p*-y25. | 2 | 41 | 96 | | — | | | | | | | | |
| p*-d pond well. | 3 | 35 | 100 | | — | | | | | | | | |
| p-g pond well(16-77). | 3 | 43 | 100 | | — | 52139.0 | 0.39 | 28738.0 | 0.20 | 37321.7 | 0.28 | 96256.7 | 0.72 |
| p*-m pond well. | 3 | 34 | 101 | | — | | | | | | | | |
| p-bassett3 well(well 12). | 2 | 43 | 101 | | — | | | | | | | 61497.3 | 0.46 |
| p-damm/joel street well. | 2 | 37 | 109 | | — | 41443.9 | 0.31 | 21390.4 | 0.18 | 29746.0 | 0.22 | 100267.4 | 0.75 |
| p-flaxpond 9well(site 75). | 2 | 40 | 111 | | — | 41443.9 | 0.31 | 21390.4 | 0.16 | 29746.0 | 0.22 | 133689.8 | 1.00 |
| well 21. | 2 | 33 | 112 | 21390.4 | 0.16 | 61497.3 | 0.46 | 26738.0 | 0.20 | 41221.0 | 0.31 | 86898.4 | 0.65 |
| well 22. | 2 | 33 | 111 | 24064.2 | 0.18 | 82887.7 | 0.62 | 24064.2 | 0.18 | 48574.0 | 0.36 | 105815.0 | 0.79 |
| p-no name near well 21. | 2 | 33 | 110 | | — | 41443.9 | 0.31 | 21390.4 | 0.16 | 29746.0 | 0.22 | 86898.4 | 0.65 |
| well 24.(r) | 2 | 41 | 97 | 16042.8 | 0.12 | 36096.3 | 0.27 | 37433.2 | 0.28 | 36876.1 | 0.28 | 66844.9 | 0.50 |
| well 23.(r) | 1 | 39 | 98 | 22727.3 | 0.17 | 40107.0 | 0.30 | 37433.2 | 0.28 | 38547.2 | 0.29 | 76203.2 | 0.57 |
| | 24 nodes | | | | 3.30 | | 10.80 | | 5.24 | | 7.56 | | 18.04 |

p- proposed source, included in model runs.

P*- proposed for future, not included in model runs.

(r) Use restricted by DEP, Water Management Act.

# EAST CAPE MODEL WELLS

Updated dec 1992 - jan 1993, proposed pumping based on October - December 1992 interviews with water supply officials; 1988-90 pumping based on DEP water supply statistical report data.

| Orleans Water Department | Depth | Row | Col. | Existing 88-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 1. | 2 | 15 | 56 | 16042.8 | 0.12 | 32085.6 | 0.24 | 14705.9 | 0.11 | 21947.4 | 0.18 | 88898.4 | 0.65 |
| wells 2, 3. | 2 | 16 | 56 | 40107.0 | 0.30 | 64171.1 | 0.48 | 34759.4 | 0.28 | 47014.3 | 0.35 | 159090.9 | 1.19 |
| well 4. | 2 | 18 | 55 | 25401.1 | 0.19 | 44117.6 | 0.33 | 21390.4 | 0.16 | 30860.1 | 0.23 | 114973.3 | 0.86 |
| well 5. | 2 | 19 | 56 | 14705.9 | 0.11 | 24064.2 | 0.18 | 12032.1 | 0.09 | 17045.5 | 0.13 | 62834.2 | 0.47 |
| well 6. | 2 | 17 | 55 | 32085.6 | 0.24 | 70855.6 | 0.53 | 41443.9 | 0.31 | 53698.8 | 0.40 | 133689.8 | 1.00 |
| p-well 7. | 2 | 20 | 58 | 0.0 | — | 70855.6 | 0.53 | 41443.9 | 0.31 | 53698.8 | 0.40 | 133689.8 | 1.00 |
| p-well 8. | 2 | 18 | 58 | 0.0 | — | 70855.6 | 0.53 | 41443.9 | 0.31 | 53698.8 | 0.40 | 100267.4 | 0.75 |
| | 7 nodes | | | | 0.96 | | 2.82 | | 1.55 | | 2.08 | | 5.92 |

p- proposed source, included in model runs.

| Dennis Water Department | Depth | Row | Col. | Existing 1988-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| main station. | 1 | 28 | 18 | 42780.7 | 0.32 | 64171.1 | 0.48 | 20053.5 | 0.15 | 38435.8 | 0.29 | 135026.7 | 1.01 |
| wells 1, 2, 3. | 1 | 25 | 21 | 25401.1 | 0.19 | 40107.0 | 0.30 | 12032.1 | 0.09 | 23729.9 | 0.18 | 133689.8 | 1.00 |
| well 4. | 1 | 22 | 18 | 9358.3 | 0.07 | 22727.3 | 0.17 | 4010.7 | 0.03 | 11809.3 | 0.09 | 33422.5 | 0.25 |
| well 5. | 1 | 27 | 20 | 18716.8 | 0.14 | 40107.0 | 0.30 | 21390.4 | 0.18 | 29188.9 | 0.22 | 86898.4 | 0.65 |
| well 6. | 1 | 22 | 17 | 2673.8 | 0.02 | 17379.7 | 0.13 | 14705.9 | 0.11 | 15820.0 | 0.12 | 29411.8 | 0.22 |
| well 7. | 1 | 24 | 22 | 20053.5 | 0.15 | 37433.2 | 0.28 | 9358.3 | 0.07 | 21058.1 | 0.18 | 86898.4 | 0.65 |
| well 8. | 1 | 24 | 23 | 9358.3 | 0.07 | 28074.9 | 0.21 | 4010.7 | 0.03 | 14037.4 | 0.11 | 88844.9 | 0.50 |
| well 9. | 2 | 22 | 20 | 24064.2 | 0.18 | 40107.0 | 0.30 | 10695.2 | 0.08 | 22950.1 | 0.17 | 100287.4 | 0.75 |
| well 10. | 1 | 25 | 23 | 26738.0 | 0.20 | 64171.1 | 0.48 | 36096.3 | 0.27 | 47794.1 | 0.38 | 135026.7 | 1.01 |
| well 11. | 2 | 23 | 18 | 16042.8 | 0.12 | 40107.0 | 0.30 | 20053.5 | 0.15 | 28409.1 | 0.21 | 96256.7 | 0.72 |
| well 12. | 1 | 26 | 23 | 34759.4 | 0.26 | 48128.3 | 0.36 | 36096.3 | 0.27 | 41109.6 | 0.31 | 153743.3 | 1.15 |
| well 13. | 2 | 32 | 23 | 20053.5 | 0.15 | 40107.0 | 0.30 | 21390.4 | 0.16 | 29188.9 | 0.22 | 96256.7 | 0.72 |
| well 14. | 1 | 22 | 22 | 17379.7 | 0.13 | 40107.0 | 0.30 | 8021.4 | 0.06 | 21390.4 | 0.18 | 86898.4 | 0.65 |
| well 15. | 1 | 22 | 21 | 26738.0 | 0.20 | 54812.8 | 0.41 | 12032.1 | 0.09 | 29857.4 | 0.22 | 135026.7 | 1.01 |
| well 16. | 1 | 23 | 21 | 20053.5 | 0.15 | 37433.2 | 0.28 | 21390.4 | 0.16 | 28074.9 | 0.21 | 114973.3 | 0.86 |
| well 18. | 2 | 19 | 18 | 32085.6 | 0.24 | 44117.6 | 0.33 | 14705.9 | 0.11 | 28960.8 | 0.20 | 133689.8 | 1.00 |
| p-well 19. | 2 | 20 | 15 | 0.0 | — | 44117.6 | 0.33 | 53475.9 | 0.40 | 49576.6 | 0.37 | 133689.8 | 1.00 |
| | 17 nodes | | | | 2.59 | | 5.28 | | 2.39 | | 3.59 | | 13.15 |

p- proposed source, included in model runs.

# EAST CAPE MODEL WELLS continued

| Brewster Water Department | Depth | Row | Col. | Existing 1988-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| well 1, 2. | 2 | 22 | 47 | 92246.0 | 0.69 | 68181.8 | 0.51 | 52139.0 | 0.39 | 58823.5 | 0.44 | 360962.6 | 2.70 |
| well 3. | 2 | 20 | 49 | 49465.2 | 0.37 | 46791.4 | 0.35 | 25401.1 | 0.19 | 34313.7 | 0.26 | 187165.6 | 1.40 |
| p-well 4. | 3 | 21 | 30 | 0.0 | — | 46791.4 | 0.35 | 25401.1 | 0.19 | 34313.7 | 0.26 | 133889.8 | 1.00 |
| p-well 5. | 2 | 24 | 30 | 0.0 | — | 46791.4 | 0.35 | 25401.1 | 0.19 | 34313.7 | 0.26 | 133889.8 | 1.00 |
| p-wells 6,7. | 2 | 21 | 49 | 0.0 | — | 97593.6 | 0.73 | 50802.1 | 0.38 | 70298.8 | 0.53 | 267379.7 | 2.00 |
| | 5 nodes | | | | 1.06 | | 2.29 | | 1.34 | | 1.74 | | 8.10 |

p- proposed source, included in model runs.

| Chatham Water Department | Depth | Row | Col. | Existing 1988-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indian hill well. | 2 | 35 | 52 | 48128.3 | 0.36 | 17379.7 | 0.13 | 10695.2 | 0.08 | 13480.4 | 0.10 | 153743.3 | 1.15 |
| south chatham well field. | 2 | 37 | 44 | 42780.7 | 0.32 | 54812.8 | 0.41 | 32085.6 | 0.24 | 41555.3 | 0.31 | 280748.7 | 2.10 |
| training field road well. | 2 | 33 | 53 | 26738.0 | 0.20 | 14705.9 | 0.11 | 10695.2 | 0.08 | 12368.3 | 0.08 | 88888.4 | 0.65 |
| well 8. | 2 | 35 | 45 | 0.0 | — | 58823.5 | 0.44 | 33422.5 | 0.25 | 44008.2 | 0.33 | 133889.8 | 1.00 |
| well 7. | 2 | 34 | 45 | 0.0 | — | 60160.4 | 0.45 | 34759.4 | 0.26 | 45343.1 | 0.34 | 133889.8 | 1.00 |
| p-golden triangle well. | 2 | 34 | 52 | 0.0 | — | 20053.5 | 0.15 | 0.0 | 0.00 | 8355.6 | 0.06 | 48128.3 | 0.36 |
| p-goodwin well. | 2 | 33 | 49 | 0.0 | — | 10695.2 | 0.08 | 0.0 | 0.00 | 4456.3 | 0.03 | 77540.1 | 0.58 |
| | 7 nodes | | | | 0.88 | | 1.77 | | 0.91 | | 1.27 | | 8.84 |

p- proposed source, included in model runs.

| Harwich Water Department | Depth | Row | Col. | Existing 1988-90 pumpage cfd | mgd | Projected 2020 In Season Pumpage cfd | mgd | Projected 2020 Off Season Pumpage cfd | mgd | Projected 2020 Avg Annual Pumpage cfd | mgd | Pumping Capacity cfd | mgd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| main station. | 1 | 36 | 40 | 17379.7 | 0.13 | 14705.9 | 0.11 | 6684.5 | 0.05 | 10026.7 | 0.08 | 192513.4 | 1.44 |
| wells 1, 2. | 1 | 34 | 40 | 42780.7 | 0.32 | 42780.7 | 0.32 | 18716.8 | 0.14 | 28743.3 | 0.22 | 184492.0 | 1.38 |
| wells 3, 4. | 2 | 35 | 40 | 38770.1 | 0.29 | 37433.2 | 0.28 | 16042.8 | 0.12 | 24955.4 | 0.19 | 244652.4 | 1.83 |
| wells 5, 8. | 2 | 35 | 43 | 45454.5 | 0.34 | 42780.7 | 0.32 | 18718.6 | 0.14 | 28743.3 | 0.22 | 183155.1 | 1.37 |
| well 7. | 2 | 36 | 44 | 26738.0 | 0.20 | 24064.2 | 0.18 | 10695.2 | 0.08 | 16265.6 | 0.12 | 105615.0 | 0.79 |
| wells 8, 9. | 2 | 30 | 50 | 52139.0 | 0.39 | 133689.8 | 1.00 | 56149.7 | 0.42 | 88458.1 | 0.66 | 192513.4 | 1.44 |
| p-well 10. | 3 | 25 | 29 | 0.0 | — | 36096.3 | 0.27 | 14705.9 | 0.11 | 23618.5 | 0.18 | 100267.4 | 0.75 |
| p-well 13. | 2 | 28 | 29 | 0.0 | — | 36096.3 | 0.27 | 14705.9 | 0.11 | 23618.5 | 0.18 | 100267.4 | 0.75 |
| p-well 11. | 2 | 27 | 50 | 0.0 | — | 36096.3 | 0.27 | 14705.9 | 0.11 | 23618.5 | 0.18 | 100267.4 | 0.75 |
| p-spruce road well. | 2 | 26 | 44 | 0.0 | — | 36096.3 | 0.27 | 14705.9 | 0.11 | 23618.5 | 0.18 | 100267.4 | 0.75 |
| p-well 12. | 2 | 27 | 49 | 0.0 | — | 36096.3 | 0.27 | 17379.7 | 0.13 | 25178.3 | 0.19 | 100267.4 | 0.75 |
| | 11 nodes | | | | 1.67 | | 3.56 | | 1.52 | | 2.37 | | 12.00 |

p- proposed source, included in model runs.